TECHNICAL BULLETIN NO. 796 • DECEMBER 1941

Methods of Forecasting Timber Growth in Irregular Stands

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UNITED STATES DEPARTMENT OF AGRICULTURE, WASHINGTON, D. C.

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INTRODUCTION

Timber resources are renewable only through the growth of trees. The growth and reproduction of merchantable timber, and the consequent changes in growing stock, constitute the foundation of forest management. Because a consideration of these factors is essential in planning the continuity of a public or private forestry enterprise, handling them properly is of paramount importance and should be supervised by competent professional foresters. Predictions of sustained timber growth are needed not only in general terms for the broad public classification of forest lands in attempts to place economic planning on a sound and practical basis, but also in more precise terms for the more restricted and comparatively short-time financial estimates required of managers of commercial forests.

Obviously some knowledge of growth is essential to any plan for the regulation of cutting operations. This bulletin, which deals with the problem of predicting the future growth of irregular stands over relatively short periods of time, is intended primarily for those whose task it is to hazard a forecast of forest growth in formulating man-

[1] The writer acknowledges his indebtedness to the following members of the Forest Service: B. P. Kirkland, who has pointed out the importance of growth-forecast methods in the practice of forestry; to W. E. Bond for encouragement; and to the Division of Forest Economics for basic data; to B. O. Hughes for critical review; to F. A. Ineson, the most active proponent of the dispersion method; to R. R. Reynolds, an early advocate of the hypothesis of tree movement; and to R. A. Chapman for numerous ideas concerning techniques used in the study; and also to K. E. Thomson and her associates in the Works Progress Administration for assistance with the computations.

agement policies and plans. Dependable information on periodic growth in volumes is constantly needed in timber management, particularly where an effort is being made to sustain yields. The observations in the present bulletin deal mainly with the question of how to do (or not to do) the necessary work. While numerical examples are drawn from experience in the southern pine region of the United States and several of the citations are to European publications, the interpretations presented should be widely useful in forest management throughout the Temperate Zone.

Many schemes for the determination of forest growth have failed either because of their inadequacy or because of the difficulty of properly applying them to a concrete problem. Thus discredit has come both to the overly simple mean-sample-tree method of early days and to some of the later more involved attempts to correct normal-yield tables to apply to actual stands. Much more promising is the recent research by Duerr and Gevorkiantz (*12*)[2] on the problem of growth in uneven-aged timber, which correlates average per-acre figures for: (1) Volume, (2) main-stand diameter,[3] (3) age, (4) basal area (area of cross section of stem in square feet), and (5) board-foot (or cubic-foot) square-foot ratio. The growth prediction rests on analysis of the interrelationship of these factors. In the present study, however, the writer does not attempt any such fundamental analysis; the purpose is to outline procedures simple enough for practical application and appropriate for local conditions.

Certain items of information needed in projecting these stands, such as normal rates of loss from natural mortality of trees, can be determined conclusively only by the exceedingly slow and expensive process of reexamining numerous permanent sample plots over long periods. Fortunately, the net annual rate of current or periodic increment (growth minus loss) in board feet or cubic feet can be estimated promptly from an extensive sampling process, using temporary plots or strips such as are commonly employed by timber cruisers. Stand data and increment borings, obtained on the random or mechanical system of sample plots customary in volume inventories, provide the most economical means of obtaining the data needed for studies of growth. In these studies size distribution as well as volume of timber may profitably be forecast because of the great variation in values of different-sized trees.

Briefly, this bulletin includes a discussion of numerous specific questions connected with the general problem. The subject of predicting timber growth has not yet reached (and may never reach) a stage of development that might justify the discussion and recommendation of a single forecast method to the exclusion of all others. Accordingly, this paper is intended to encourage critical consideration of the advantages and disadvantages of several optional procedures.

In commenting on rough approximations, some of the pitfalls in using growth percent are pointed out. Greater space is devoted to several variations of the stand-table-projection method. As many foresters are not yet sufficiently familiar with forecasting procedure, the principal steps of this widely applicable method are

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[2] Italic numbers in parentheses refer to Literature Cited, p. 48.

[3] Unless otherwise indicated, the word diameter in this bulletin refers to the diameter of trees measured outside the bark at a point 4½ feet above ground.

presented in detail. Examples of forecasting by this and other methods include concrete illustration of simple forms in which to set up a stand projection. Comments are made on some of the fallacies commonly involved in forecasting growth, and specific evidence is advanced to indicate the futility of using too much detail in the computing procedures. Numerical results of using the same data in various procedures are compared. A method of converting a stand table using one diameter-class interval to the equivalent table using another class interval is illustrated. Assumptions, hypotheses, and some possible sources of errors of unknown magnitude, e. g., the failure to make correct allowance for mortality or for acceleration or deceleration of growth, are discussed in some detail because they may cause forecasts to hit far from the mark. The recurring-inventory method of determining growth is reviewed because it promises to become the principal means of control in the more intensive management of irregular forests.

APPROXIMATIONS OF TIMBER-GROWTH RATES

Nearly everyone appears to be more or less guilty of making hasty generalizations from scanty or inadequate data. Rough and ready calculations are used not only by those unable to handle other methods, but also by technicians for rapid and tentative approximation. No attempt need be made to discourage toying with rules of thumb or other very simple methods, provided their limitations are recognized and not too much reliance is placed on the results obtained.

Approximations of diameter growth may be had from cut stumps, which have serious limitations as gages, however, and should be used for this purpose only when certain precautions are observed. Partial cuts are usually selective, so that an estimate of growth based on stumps cannot represent the stand that remains. The pronounced effect of butt swell on measurements at stump height exaggerates the normal width of annual rings; consequently, ratios of diameters at stump and breast height are needed to correct this error. Finally, irregularity and eccentricity of low-cut stumps are confusing, and all measurements of stump growth if used at all should be computed from the average of several radii. Obviously, stump analyses are not suited for precise work.

Information as to actual growth rates on comparable sites may be helpful in detecting serious errors in growth estimates that might otherwise pass unnoticed. For example, on the better sites, in second-growth loblolly and shortleaf pine stands as now stocked, the rates of annual volume increment commonly vary from 4 to 9 percent. In many typical young, well-established (but understocked) forests the average rate of diameter growth (expressed in inches per decade) tends to decrease progressively because of the gradual closing-in of the stands.[4]

Computation of Growth Percent

Since the areas of circles increase as the squares of their radii, one may set up a formula for annual percentage growth in basal

[4] This natural deceleration of diameter growth can, and usually should, be reduced or eliminated by applying proper cutting practices.

area as follows: $\frac{100\ (d+0.2R)^2}{d^2}-100$, where R=radial growth in inches inside bark in 10 years (the usual measurement taken in studies of diameter growth), d=the present diameter, and the expression $(d+0.2R)$=diameter 1 year from now. This formula, which disregards bark growth, may be stated approximately in the simple form $\frac{40R}{d}$. If radial increment in bark (i. e., growth minus loss from sloughing off) be taken as 10 percent of the total radial increment, as in loblolly pine, the shortened formula becomes approximately $\frac{44R}{d}$. Such a formula, however, can approximate volume growth only where trees are not changing in form and height, and where no new trees are growing into the main stand; as this is seldom the case, its practical value is very limited.

Herrick (*23*) suggests that future diameter may be predicted on the assumption that periodic growth in basal area tends to remain fairly constant, and he presents the formula $F=\sqrt{2D^2-P^2}$, where D=present diameter, F=future diameter, and P=past diameter (as many years in the past as F is in the future). In this simple formula the basic assumpation is reasonable; at least it appears to hold for ponderosa pine and it should apply also to other species in which diameter growth does not culminate at an early age (*3*).

If and when—in spite of its limitations, discussed in the following sections—percentage is used in studying the growth and accumulation of wood capital, certain mathematical formulas and tables are useful. A comparison of several of the percentage methods of predicting timber growth was made by Rudolf (*32*), who found the results of various formulae in close agreement. If desired, the results of more intensive studies of periodic growth also can be expressed easily in terms of percentage. By way of illustration, the periodic growth shown in table 2, page 18,[5] will be expressed in percentages. Growing stock at the end of 5 years was forecast at 135 percent of that at the start (total of line 14 divided by total of line 15), or an increase of 7.0 percent annually by simple interest. If compound-interest tables are available, such as appear commonly in textbooks on forest mensuration, the equivalent compound rate, 6.2 percent, may be found by interpolating for the factor 1.35 opposite 5 years. If such tables are not available, the computation may be made by means of logarithmic tables. The compound rate p may also be derived from the simple interest rate R by using the formula: $p=100\ (\sqrt[n]{1+0.01nR}-1)$. This last formula is the basis for a series of curves (one for 5 years, another for 10 years, etc.; see fig. 1), showing the relation between simple and compound rates of interest for identical yields in periods indicated, thus providing a graphic means of instantaneous conversion.

Growth percentage perhaps is most commonly applied in rough approximations, when no detailed stand-table forecasts exist as a

[5] In this bulletin, the growth predictions (presented later) which are based on the detailed projection of stand tables are assumed to be the most accurate ones available, and are therefore used as a yardstick in gaging the success of rough approximations (discussed first) often using the same data. Hence, it is necessary to refer forward occasionally to tables containing data that are treated more fully in subsequent sections.

basis for the estimate. Usually only a few increment borings and a general idea of the average diameter of the trees are available in such cases, but growth percentages preferably should be computed separately by diameter classes. By neglecting height growth, form changes, and bark thickness, the well-known foresters' simple-interest formulas (Schneider's and Pressler's) are conservative enough to approximate roughly compound-interest rates. As pointed out by Tischendorf (*35*), however, it should be kept in mind that while these formulas give fairly close results for middle-aged and mature trees, the errors are considerable for small, fast-growing trees.

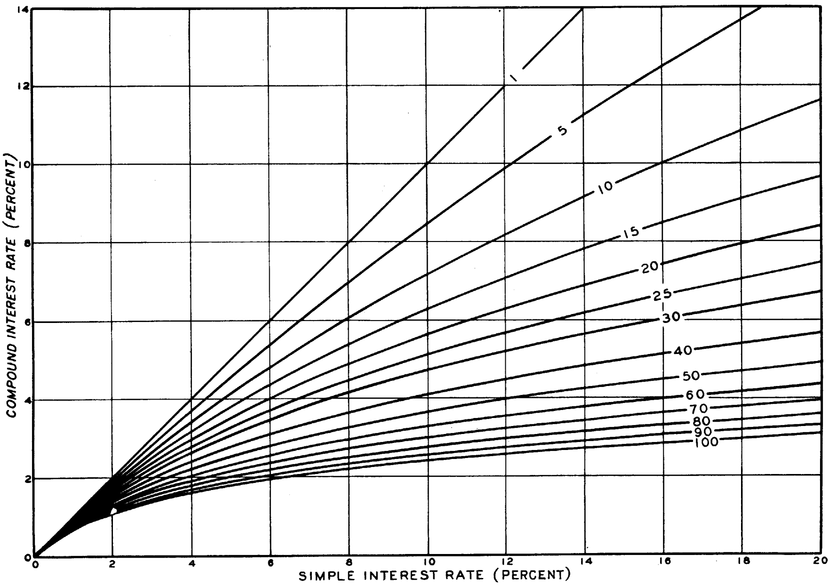

FIGURE 1.—Relation between simple and compound rates of interest for identical yields in the numbers of years indicated by figures on the curves. These curves represent the formula $p=100\ (\sqrt[n]{1+0.01nR}-1)$ where p equals compound interest rate, R equals simple interest rate, and n equals period in years. With interest compounded annually there is no difference in yield at the end of 1 year (curve 1). The chart indicates, for example, that for a given sum accumulating over a period of 20 years (curve 20) a simple interest rate of 6 percent is needed to equal the yield at 4 percent compound interest.

Among the various attempts made to improve on simple formulas for facilitating the determination of growth percentage on cut stems is that recently described by Gascard (*16*), who derives the following formula:

$$p=\frac{100}{m}\times\frac{(2n-1)}{n^2},\text{ where}$$

p=annual growth percent of sample trees; m=number of years in growth period; $n=\frac{R}{b}$; R=average radius (pith to periphery); b=part of radius traversing the increment zone (the growth of the last m years, e. g., 5, 10, or 20). Again using the figures derived from table 2, page 18, showing that average trees increased in diameter from 9.5 to 10.5 inches in 5 years, $p=3.6$ percent. This percentage seems low (compared with 6.2 percent derived above from data in table 2) because it includes only that portion of volume growth associated with increase in the basal area of saw timber—in our example not over 60 percent of the total growth. The remaining increment is associated with height growth, increases in form class, if any, and the material addition of volume in new trees (ingrowth) not originally considered because they were below sawlog size at the beginning of the period.

Simple growth formulas were recently presented for use in the Lake States by Gevorkiantz and Duerr [6] as follows: Let P=annual growth percent, g=expected 10-year increment in d. b. h. (inches), and D=present d. b. h. (inches). Then the percentage of cubic-foot growth $P=24\frac{g}{D}$, and the percentage of board-foot (Scribner) growth $P=25\frac{g}{D}$. These formulas, which assume uniformity in standards of utilization, are based on volume tables that show a progressive increase in merchantable length with increases in diameter. Where the merchantable length was fixed for life by branch structure, as is often the case in hardwood trees, the above formulas were found to give too high an estimate. In such cases the authors applied the formula $P=23\frac{g}{D}$. If k, a factor varying with the rapidity of height growth, be substituted for the numerical constants in this formula, it should also be useful where utilization standards differ (but are constant during the growth period).

An interesting short method of computing growth was used on the Minnesota Land Economic Survey and reported by Wijkstrom (*36*) in 1930. According to Jonson's formulas, which he employs,

$$P_g=\frac{100}{n}\left(1-\frac{d^2}{D^2}\right), \text{ and } P_{fh}=\frac{100Z_h}{H+k}$$

where P_g=growth percentage associated with increase in basal area; n=number of years in period; d=past diameter (n years ago); D= present diameter outside bark (inches), (or in predicting d=present and D=future diameter); P_{fh}=growth percentage associated with changes in form-height; Z_h=mean annual height growth from site index (feet); H=average height of stand (feet); and $k=8.2$, a constant. Using and supplementing the data from table 2: $n=5$, $H=74$, $Z_h=1.54$, $D=10.5$, and $d=9.5$ for diameter with growth of 1 inch in 5 years. Then by the above formulas, $P_g=3.63$ (the same as from Gascard's formula) and $P_{fh}=1.87$, indicating a total percentage of 5.5. This seems low; according to subsequent detailed calculations the growth rate is at least 6 percent (table 3, p. 24). If the rate of 5.5 percent be increased by one-fourth for ingrowth, the result is approximately 6.9 percent simple interest. For a 5-year period, this is equivalent to the compound rate of 6.1 shown in table 3. But an arbitrary addition of one-fourth for ingrowth should not be necessary when data for 6- and 8-inch trees are included. If only saw-timber trees (i. e., trees 9.5 inches d. b. h. and larger) are included in basic

[6] GEVORKIANTZ, S. R., and DUERR, WM. A. METHODS OF PREDICTING GROWTH OF FOREST STANDS IN THE FOREST SURVEY OF THE LAKE STATES. U. S. Dept. Agr., Forest Serv., Lake States Expt. Sta., Econ. Note 9, 59 pp. 1938. [Processed.]

data, then $P_g=3.06$ and $P_{fh}=1.87$, which together $=4.69$. Adding one-fourth to this gives 6.16 simple or 5.3 percent compound interest, a figure smaller than the previous one. In order to match the 6.9 simple or 6.1 compound percentage of table 3 by adjusting the constant in this case, k would have to equal -17 instead of $+8.2$, but no rationalization is available to justify such a change, nor is there any assurance that any general increase in accuracy would result. If the local computations are essentially correct, therefore, further verification appears to be necessary before much reliance can be placed on formulas and short-cut methods from other regions in computing local rates of timber growth.

Caution Needed in Using Percentage Methods

This treatment of increment in wood as compound interest on volume is one of the simplest of the nonintensive methods of estimating growth in irregular forests. A percentage rate may be approximated merely on the assumption that the timberlands and timber stands to be managed are very similar to others of known capacity for growth. As mentioned in an earlier paper (*7*), such indiscriminate approximations are unreliable at best, and should not be trusted until checked against growth data gathered from the timber property itself. To do this in a rough and crude way is a very easy task. Average rates of diameter growth can be applied to the average-sized tree to indicate its probable size 10 years hence. Either due allowance for volume losses from mortality of trees must be made, or it must be assumed, with some uncertainty, that any unsalvaged portion of these volumes will be offset by the indefinite gains surely obtainable from accelerated growth under management. Allowance must be made for ingrowth, i. e., increases in volume resulting from trees of premerchantable size growing into saw timber or other material recognized as merchantable. The expected change in volume for the coming decade can then be expressed approximately as a percentage, of which one-tenth will represent the current annual increment by simple interest. The equivalent compound annual interest rate may be found more useful in applying these approximations.

Although it is sometimes advantageous thus to regard the increase in wood volume in forest stands as compound interest on wood capital, a full realization of the nature and limitations of percentage as a means of expressing growth is essential.[7] If thoughtlessly regarded as a fixed unit of measure, percentage can be very deceptive. Being merely the ratio of increment over volume (a fraction whose denominator constantly increases), a tree's growth percent normally declines progressively, though growing conditions and actual volume growth may change very little. Because of this decline, any use of percentage derived from past growth is likely to overestimate future growth of the same stand. The longer the period forecast, the more this error will be aggravated, particularly if compound interest (which employs geometrical progression) is being used instead of simple interest. Any percentage derived from one stand will be incorrect when applied to another stand, unless the trees in each are similarly distributed among the various diameter classes. Further-

[7] Personal letter from H. H. Chapman to the author, May 2, 1939.

more, a high growth percent is often associated, perhaps unfortunately, with undesirable rather than desirable stand conditions. For instance, the smaller the trees left after a cutting, the larger will be the growth percent and the smaller the actual growth.

For a premerchantable tree, the growth percent is often extremely high in early life because of the relatively small basic volume, yet increment in realizable value may be close to zero (potential only). On the other hand, a large, sound timber tree with a long, straight, clear, full bole normally has a very high rate of value increment even though it may show a perceptible decrease in rate of diameter growth. This is because of the relatively high quantity and the superior quality of its wood increment produced on a relatively large basic volume, in spite of its relatively low growth percent.

If change in form and height are neglected, growth in cross-sectional area (basal area) represents growth in volume. Trees growing 2 inches d. i. b. in 10 years and with nearly all annual rings 0.1 inch wide, may be regarded as growing very uniformly. Annual increment expressed in percent of basal area, however, would be far from uniform even on such trees; for example, 1-inch trees would show an annual increment of 44 percent, 10-inch trees of 4 percent, 20-inch trees of 2 percent, and 40-inch trees of 1 percent. Similarly, if a tree were to maintain a constant basal-area growth of 0.05 square foot (inside the bark), in growing from 11 to 24 inches d. i. b., annual rings would progressively decrease in width from 0.2 inch to 0.1. Obviously the growth of individual trees expressed in percent requires careful interpretation.

In applying growth percent to young forests in which yields are to be built up by conservation of growing stocks, a decline in percent of volume growth seems inevitable. In spite of accelerated diameter growth from selective cutting, the growth percent is certain to decrease with increase in the average size of trees. This may be offset by the higher volume and greater value of annual yields. In any event it should be kept in mind that percentage is thoroughly reliable only as the static expression of an existing momentary relationship. It should not distract the forester's attention from (or distort his view of) one of his major objectives, viz, quantity and quality production per acre per year expressed in absolute, not relative units.

Some of the disadvantages in applying percent of volume growth to individual trees apply with less force to forests, especially to irregular forests in which all size-classes are well represented. Even in well-managed forests, however, the growth percent cannot indicate financial relationships, because other vital economic factors, such as land, improvements, and profits, are not considered.

It may be held justly that refinement in the first studies of growth of an unmanaged forest is unwarranted, because the amount of growth can be changed so readily and so materially through management. Nevertheless, many of the short methods so far described may be rejected in their present form as inadequate for or unsuited to the needs of forest owners who seriously contemplate forestry.

STAND-TABLE-PROJECTION METHOD

Sampling Growth

Both present-day stand tables and the growth data needed to project them into the future are obtained from timber cruises. Girard and Gevorkiantz,[8] in discussing various methods of cruising, list the advantages and disadvantages of strip versus plot systems, and make suggestions as to intensity of sampling in order to keep errors within reasonable limits. Instructions are given for the construction and application of volume tables. The manual also supplies certain numerical helps ("taper index," "taper factors," and "form-diameter," with tables showing their interrelationships) together with a method of using them for scaling the volume of whole trees without regard to individual logs contained in them. Care in this phase of the work is essential, since volume determinations, like the system of sampling, must fit local conditions if the forecasts are to be free from unintentional bias.

In general, satisfactory results may be expected from studies of current periodic growth based on samples of standing timber taken at breast height (4½ feet above the ground). The Swedish (Pressler's) increment borer is convenient for cruisers in sampling the growth of all sizes and classes of the principal species of timber. With the cross section of a tree hidden from view, the difficulty of allowing for eccentricity is increased, but this disadvantage is more than offset by the larger and more representative sampling of the entire stand usually made possible with this instrument. Inaccuracy resulting from guesswork in striving to recognize and attempting to count annual rings that are more or less indistinct (or too small to distinguish without a lens) is all too common. Such mistakes tend toward cumulative rather than compensating error, and may cause average rates of growth to be overestimated.

A report by Glock (*18*) contains hints useful in the interpretation of tree rings. He discusses such matters as how to detect absent rings; how to recognize all phases of locally present, merging, and partially developed rings; how to resolve doubles; and how to recognize midlines. The elimination of all uncertainty in ring counts, difficult as it is when numerous disk sections are available, is practically impossible when increment cores alone are used, and it may even be better to use an ax in inspecting the rings of dead trees. Nevertheless, precaution to reduce the inaccuracy of counts made on cores is essential. As pointed out by Glock, an annual ring extends in width from the sharp outside of one to the sharp outside of the next. False rings as a rule do not terminate outwardly in faces so sharp and abrupt as those of true rings. Sometimes a thin layer of light-colored wood, composed of thin-walled cells resembling springwood, is formed in summer. The formation of narrow layers of thick-walled cells in midspring is another possibility. In either case the narrow out-of-season line produced may be very confusing

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[8] Girard, James W., and Gevorkiantz, Suren R. timber cruising. U. S. Forest Serv. 160 pp., illus. 1939. [Mimeographed.]

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in making ring counts. Then Glock's rule regarding double or false rings may be useful:

> If a thin band of summer wood lies closely inside a thick band of summer wood, the thin one is part of a double; but if the thin band lies immediately outside the thick band, the thin one is part of a separate annual ring.

If the survey that is used for estimating the volumes of timber stands covers the entire forest property systematically, it provides an excellent opportunity to study the growth of timber, but it must be remembered that unless appropriate methods are used in stand forecasting and certain precautions taken, the results of this detailed work will be no more dependable than those from some simpler method. Furthermore, systematic or mechanical methods of sampling, commonly used by timber cruisers in gridironing a forest with strips or plots located at regular intervals, do not permit of reliable estimates of the magnitude of sampling errors. This paper does not, however, include suggestions for truly random sampling to make such estimates possible.

In sampling the growth rate of trees by counting the annual rings on cores removed with increment borers, certain precautions are necessary to secure a truly representative sample. For example, in line-plot cruising the tree nearest the center of each plot is often specified for measurement of growth. This method of selection is undesirable because it results in sampling the less dense stands of trees more thoroughly than the more dense. The open stands not only contain considerably fewer trees per acre but also may show an appreciably greater growth in diameter.

A better plan is to provide for the distribution of growth samples according to the relative abundance of trees in the various merchantable size classes. In line-plot timber cruising, this is most easily done at each estimating station on supplementary small plots of uniform size such as are frequently used for seedling counts. Boring every tree of merchantable size on such plots (plus all trees in one or two of the premerchantable diameter classes, in order to gage ingrowth) places the sample on an area basis and automatically provides for weighting the sample properly according to the number of trees in the various diameter classes. This method will automatically reduce the oversampling of timber in understocked areas. The fixed radius within which these samples are taken at each stop should be selected at the start so that the process of sampling may extend uniformly over the property without boring excessive numbers of trees.

A comparison of the nearest-tree basis with the area basis was made on a cruising job where all 8- to 14-inch pines were sampled on plots with a radius of 29.4 feet, all trees 15 to 19 inches in diameter on plots of 41.6 feet radius, and all trees 20 inches and larger in diameter on plots with a radius of 83.3 feet. The first tree bored at each station was the one nearest the center of the three concentric plots. Although there was not much difference in the results for diameter classes above 18 inches, averages showed the diameter growth inside bark for the past 5 years to have been 0.84 inch on the area basis and 0.94 inch on the nearest-tree basis. Thus, in this instance, the overestimate resulting from use of the older method amounted to 12 percent.

In the Southern region, the Forest Service[9] has specified radii of circular plots suitable for the gathering of growth data as follows: 52 feet 8 inches (1/5-acre) or 58 feet 11 inches (1/4-acre) for trees 20 inches in diameter and larger; 16 feet 8 inches (1/50-acre) for trees 9 to 20 inches in diameter; and 5 feet 3 inches (1/500-acre) for smaller trees. The suitability of any set of specifications for a given cruise depends on the number of plots and cores needed to meet the different requirements of studies of varying intensity.

In practical work these requirements have usually been assumed rather than estimated by statistical methods. When only a moderate or scanty number of borings has been made, estimates based solely upon averages for each diameter class obviously can be improved by assuming a logical trend between classes, and reading the final figures from curves drawn so as to smooth out cautiously those irregularities in the series that appear to be due solely to the small size of the sample. On the other hand, in short-term prediction, and especially where the dispersion of growth rates is to be considered, an adequate sample for each diameter class independent of all other classes is advantageous; in general, however, the necessity of having the entire sample selected on an area basis should not be overlooked in gaining this advantage alone. Growth conditions vary so much in most forests that only genuinely proportionate representation can produce reliable estimates of growth rates.

ASSUMPTIONS—GROWTH AND MORTALITY

One possible assumption is that a tree of a given size class will grow in diameter for the next decade at the same rate at which it grew in the past decade. But in forecasting the probable average growth of forests for the immediate future, another assumption is perhaps preferable—that trees of a given size class will increase in diameter during the coming decade as rapidly as trees that were in this same size class a decade ago increased during the past decade.[10] Of course this reasoning takes for granted that during these 20 years there are no radical changes in soil productivity, climate, or thrift and density of the stand. Although varying widths of rings on stumps testify to the irregular increment of individual trees, the assumption of equal rates of growth for the same size classes is useful in judging the increment of timber stands in the aggregate.

A common procedure in predicting forest growth over relatively short periods consists in contrasting the volume of timber stocks as

[9] U. S. FOREST SERVICE. A GUIDE TO TECHNICAL PROCEDURE IN MAKING FOREST MANAGEMENT PLANS IN THE SOUTH. U. S. Forest Serv., Div. of State and Private Forestry, South. Region, 36 pp. 1939. [Processed.]

[10] An objection to this assumption has been made on the ground that the trees of a given size class 10 years ago (because it then included some weak trees that died from natural causes during the decade) occupied a position which averaged lower in the scale of dominance than do the trees now in that size class (which includes, of course, only those trees sufficiently dominant at the start to have survived 10 years). Trees vigorous enough to have survived the past decade in competition with their neighbors, and consequently present to be bored in a growth-sampling survey, were among the faster growers of their size class 10 years ago. However, as the survivors usurp the space formerly occupied by trees now dead, they meet new competition from their own class and still larger trees, and some lose their dominance so that the average rate of growth declines again. While this tendency toward deceleration of growth is present in all size classes, it usually is less severe in the larger classes because they contain the more firmly established trees with a smaller fraction of the competing forest above them. In the forest example used in this bulletin, this tendency held for trees between 6 and 18 inches in diameter as indicated by a rising growth curve (see fig. 3–B). Hence, the second and more popular assumption does lead to somewhat less conservative estimates.

computed from existing stands with that computed for predicted stands, using volume, stock, and stand tables.[11] Such a procedure is reliable only for comparatively brief periods, e. g., 10 or 15 years in the North and 5 or 10 years in the South. In setting a forest stand ahead in this forecasting method, a slight reduction is made in number of trees to allow for the mortality expected during the period.

Because mortality is so variable and so difficult to measure exactly, it is appropriate to discuss our scanty, somewhat unreliable information on this important subject, together with other items or procedures regarding which we are still forced to rely on assumptions. In studying percentage methods of predicting growth, Rudolf (*32*) found that an outstanding weakness in each of several percentage methods studied was the lack of accurate means of estimating mortality in stands.

In the national survey of the forests of the lower South (1934–36), mortality rates were estimated in the following manner. The annual loss in volume from this cause was determined on the basis of a tally of dead trees in which disintegration had not progressed beyond a certain stage. For pines the criterion was that the trees should retain bark on more than 50 percent of the stem surface, and for hardwoods that they should retain branches under 5 inches in diameter. Auxiliary studies have indicated that these pines died during the past 3 years, and the hardwoods, depending on size, during the past 3 to 6 years. For ready application, average annual losses computed on this basis were expressed in percentage of total volume. Hervey (*24*) has pointed out that the length of time windthrown trees have been down may be readily checked by examining bushes and saplings which have been bent down by the falling trees. Elapsed growing seasons are then determined by counting annual nodes on sprouts and twigs from the point where the growth turned upward, or by cutting the twig at that point and counting its annual rings. Sometimes bruises on nearby trees caused by the falling of the tree in question will tell the story. It is necessary to cut into these bruises and the adjoining wood, observing the difference in ring count.

Few correlations have been established between the interval since death and the condition of the dead trees. That is perhaps the main reason why we do not yet have any very reliable means of gathering mortality data on surveys. The Appalachian Forest Experiment Station, in investigating this matter, is observing such possible criteria as: (1) The average diameter at point of rupture of the three largest broken limbs, (2) the presence or absence of numerous cracks in the bark, (3) the percentage of bark remaining on the entire bole, and (4) the percentage of bark remaining on the lowest 5 feet of bole. In pines, the first appears to have some promise; the first and last appear the most promising for hardwoods.

Another lead which might find application in a study of mortality is supplied by the technique used by archeologists in matching the ring sequence or patterns formed by tree rings in order to determine the age of logs in ancient ruins. Though caution is necessary, as noted

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[11] A volume table shows for a given locality and species the average volumes of individual trees of different sizes as computed by some uniform method. A stand table shows the average numbers of trees per acre by diameter classes. A stock table shows for a given stand the average volumes per acre contained in trees of different sizes. It may be derived by applying appropriate volume tables to stand tables.

on p. 9, it seems possible to compare the rings of sound dead trees with those of live ones to discover in what year standing sample trees died. If and when a cruiser can satisfy himself that a given ring in a dead tree was formed in the same year as a certain ring in a living tree, he can use the method. All that remains is to subtract the number of rings outside the designated ring in the dead tree from the number found outside the contemporary ring in the living tree. The remainder is the number of years ago the first tree died. This method is a possibility not yet fully explored by foresters. Any student of pine growth who contemplates using the technique of cross-dating of rings will find an interesting description of the method in the report by Glock (*18*), previously cited.

In the survey of the Crossett Experimental Forest in southern Arkansas, all trees judged to have died during the past 2 years, as indicated by their relative deterioration and retention of bark, were recorded separately by diameter classes; 2½ times this number was then assumed to be a fair estimate of mortality for the coming 5-year forecast period. Expressed as a percentage of the total numbers of trees in each separate diameter class and plotted over a diameter scale, the mortality data formed a reversed J-shaped curve that declined sharply to about 14 inches d. b. h. and then rose again for the larger diameters. In pine, 10-year mortality was relatively high for 1-inch trees, 59 percent; dropped to 2 percent for the less abundant 14-inch trees; and rose again to about 4 percent for the 20-inch trees. As the larger trees are relatively few in number, the actual number dying was very small.

These mortality data are portrayed differently and more completely in figure 2. Cumulated to show estimated losses for all timber in-and-below the diameter class shown, the data form curves that rise consistently. These curves indicate relatively small 10-year losses, less than 2 percent in pine and not over 3½ percent for the whole stand. None of these mortality data is precise, however, and the extent of inaccuracy remains undetermined.

Admittedly no satisfactorily accurate way of predicting endemic mortality rates has yet been developed, but in some situations the lack produces no untoward results. For example, in accessible, thrifty, and well-protected second-growth forests, like many in the South, the loss in merchantable growth over a short period usually is not excessive and can often be salvaged. Where dead trees can be salvaged promptly, none of the past growth is sacrificed, the loss being confined to that remaining fraction of potential future growth not automatically transferred to desirable stems released when the neighboring tree died. In these circumstances, the waste of wood is low and the interference with growth forecasts is small.

The mortality data from the experimental forest (fig. 2) have been used in making the forecasts of growth described later (see p. 17). At this point we are concerned only with the assumptions involved in that use. The mortality estimate is applied in the reduction of a stand table either before or after its projection into the future. In either case some error is involved, of course, because not all the deaths of trees occur simultaneously at the beginning or end of any definite period. Theoretically, it might be preferable to assume a steady rate of mortality during the forecast period, and to approximate the effect of this on growth by making half the deduction for mortality before projection and half of it afterward. This precaution, however, is regarded as an unnecessary refinement where, as on the experimental

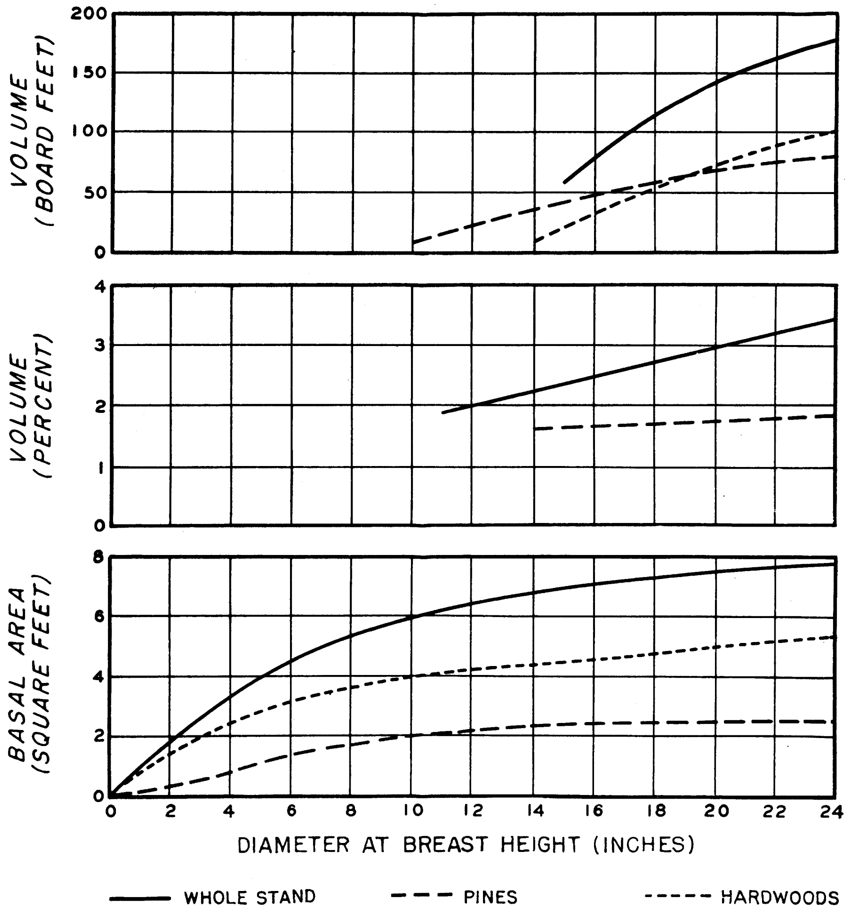

FIGURE 2.—Estimates of mortality per acre for 10 years, based on a tally of dead trees succumbing during the previous 2 years. Figures were accumulated by 1-inch diameter classes, so that readings from these curves are estimates of mortality of trees in-and-below the size indicated. Hardwood and pine mortality are shown to be not strikingly different in volume; but because of the preponderance of pine in these stands, the percentage loss in hardwoods (not shown here) was typically higher in all diameter classes—10 or 11 percent for hardwoods as against less than 2 percent for pine, resulting in an average 10-year loss ranging roughly from 2 to 3½ percent. Data are from a 20-percent inventory of a 1,000-acre tract of second-growth loblolly-shortleaf pine-hardwood forest in southern Arkansas. Of undetermined reliability, these mortality data are presented only to illustrate the information obtainable by methods described in the text.

forest, apparently mortality is so low among the merchantable size-classes and is of such minor commercial importance because of provision for prompt salvage of all dead timber. Since the effect of the error in making the entire deduction before projection is to reduce the predicted growth below the true amount, this conservative procedure is the one recommended.

All these procedures are intended to gage only the normal, not catastrophic (i. e., endemic as contrasted to epidemic), mortality regardless of causes. On the experimental forest a record obtained from complete salvage for all trees 4 inches in diameter or larger that died over a period of 2 years revealed the causes. Lightning was responsible, directly or indirectly, for 70 percent of the mortality. Although insects were the final cause of death in half the instances, their inroads could often be traced to the effects of lightning. While a fairly steady attrition from such causes may be expected, the more sweeping damage from insect epidemics or tornadoes is erratic and not ordinarily predictable.

Fires, and occasionally other destructive agents, sometimes kill appreciable quantities of material below merchantable size. On some national forests there are indications that removing a fairly heavy cut may result in the destruction of as much as 10 percent of the premerchantable stems. Usually this can be avoided, in part at least, by cutting more lightly and logging with care. Nevertheless, if heavy damage to young timber from fire or other causes is not well under control, it can easily add up to material reduction of ingrowth in a period of 10 years. Under these conditions, a forester may be justified in raising his mortality allowance above that indicated, on the basis of trees found to have died during a single short period of 2 to 6 years.

Three Concepts of Growth Movement

As a *first* option in projecting stands it may be assumed (somewhat erroneously) that all trees of a given size class will grow in the near future at an average rate for that class during the recent past. By reading a figure for the average increment of each diameter class from a curve of diameter growth, the current growth typical of each class may be obtained, and on this basis the future stand may be computed, thus completely disregarding the dispersion of individual growth rates. To ignore dispersion, however, does not necessarily invalidate the determination of net growth in volume (see p. 31).

A *second* option in projecting stands, even without having a true measure of the dispersion of growth rates within size classes, is to recognize the approximate effect of such dispersion. A useful, though not very precise, method of doing this is to make the following hypothesis of tree movement: From any given diameter class the number of trees emerging (e) is to the total number (f), as the periodic diameter growth (g) is to the diameter-class interval (i), where g and i are measured in the same units (usually inches). Thus $e:f=g:i$ and $e=fg\div i$. Expressed as a percentage, this ratio becomes $100\ fg\div i$, the "movement factor" of tables 1 and 7. If this percentage (or quotient) is 100, the assumption is then that all the trees move up one class. If the percentage is less than 100, a corresponding number moves into the next class, but the remainder stays within the present diameter class. If the percentage exceeds 100, all trees are assumed to move upward at least one class during the period, while the number of trees represented by the surplus above 100 percent is considered as moving up two classes.

Thus with a 2-inch diameter-class interval the process works out as illustrated in table 1. The number of trees moving ahead is then obtained by applying these percentages to the numbers of trees now present in each class. The growth forecast for the 5- or 10-year period is the difference between the total volume of the present stand and that of the predicted stand for the property as a whole.

The hypothesis of movement rests upon the assumptions that (1) the distribution of tree diameters within a given diameter class is even, and (2) a constant rate of increment, represented by the average for a given diameter class, maintains this evenness as each successive group of trees grows into higher diameter classes. Since these assumptions of even distribution and constant growth rates within classes are not strictly correct, inaccuracies resulting from the use of this method may be expected. Such errors may be serious in forecasting the growth of saplings and poles in irregular stands, because of the steepness of the reversed J-shaped frequency curve that represents the distribution of size classes in such stands; but since for trees of saw-timber size there is less contrast in the frequencies of occurrence of different sizes and more even distribution within size classes, for this portion of the stand the errors resulting from use of the false assumptions are probably not excessive.

TABLE 1.—*Hypothetical change of distribution in size classes of trees of varying growth rates*

Growth in diameter (inches)	Movement factor [1]	Trees moving up 2 classes	Trees moving up 1 class	Trees remaining in present class	Growth in diameter (inches)	Movement factor [1]	Trees moving up 2 classes	Trees moving up 1 class	Trees remaining in present class
	Percent	*Percent*	*Percent*	*Percent*		*Percent*	*Percent*	*Percent*	*Percent*
3.8	190	90	10	0	2.0	100	0	100	0
3.0	150	50	50	0	1.0	50	0	50	50
2.4	120	20	80	0	.6	30	0	30	70

[1] Derived in each case by multiplying the growth in inches by 100 and dividing by the class interval in inches. Thus for these 2-inch classes the movement factor is obtained by multiplying the growth figure by $\frac{100}{2}$ or 50.

In a *third* option for projecting stands in studies of growth, a deliberate attempt is made to measure the variation of growth rates within diameter classes. Where a study of changes in the relative number of trees in the several diameter classes is of prime importance, and where ingrowth in board feet is a major part of total growth, some means of gaging the dispersion of growth rates is needed. Owing to the nonnormal (often badly skewed) frequency distribution of growth rates within diameter classes, the standard deviation will probably not be satisfactory as a measure of dispersion, but percentage distribution may be computed directly from increment-core measurements if enough of them are available, and if some allowance is made for bark growth. Usually only one increment core is taken from each sample tree. A technical objection to the use of such data is the obvious tendency to exaggerate the true dispersion of growth rates. Extracting increment cores from opposite sides of a tree and averaging the core measurements might overcome the difficulty, but only at increased expense. To minimize this trouble, extraordinary care may be used to take borings only on average radii. In dealing with oval and eccentric cross sections, however, anything less than perfect guesses on this point will increase the apparent numbers of both fast- and slow-growing trees. This adds to the dispersion method an element of uncertainty not present in the methods using average growth rates, in which, at least for the greater part of stands that are largely free from ingrowth, the core measurements obtained from long and short radii tend to compensate each other. The dispersion method, however, may not overestimate ingrowth nearly as seriously as the average methods underestimate it, for the latter methods obviously recognize much too narrow a spread of individual growth rates. If ingrowth constitutes a large portion of total increment, a true measure of dispersion is more necessary in order to obtain a satisfactory estimate of the increment. When, as often happens, sampling for growth is insufficient to determine percentage movements separately by diameter classes, a single set of percentages may be obtained for the stand as a whole, and then applied uniformly to each class on the assumption that the classes are very similar in dispersion of growth. This assumption, like several previous ones, is not exactly correct, but the resultant inaccuracies within the various diameter classes offset one another to some extent and thus reduce the final error.

Obviously all of the assumptions discussed are open to the objection that each fails in some respect to depict growth movements of timber trees exactly as they are known to occur in nature. Consequently none of the three suggested options for projecting stands into the future—each of which is useful—can be recommended as universally suitable. The first is the simplest, and is satisfactory when the forecaster desires nothing more than a fair estimate of volume growth for the entire stand. The second is not so complex to use as to describe, and it provides some conception of the future distribution of tree sizes within the stand. The third requires appreciably more field work in taking increment cores from numerous sample trees, but it provides a direct estimate of dispersion in tree movements and should yield a better estimate of the consequent future distribution of trees in the various size classes. Where such information is not essential, this costly procedure should be avoided. With precautions to minimize common errors from sampling and other sources, including those in the basic assumptions reviewed in preceding pages, the stand-table-projection method, using some one of the three optional ways of projecting stands, is apparently suitable for practical use in preliminary forecasts of the volume of timber growth on forest properties.

Steps in the Projection of Stand Tables

In the procedure of projecting stand tables, 17 numerical steps, each an item or line in table 2,[12] are more or less self-explanatory when supplemented by figure 3, using as an illustration the data for pine timber in natural second-growth stands. Those who wish to apply the procedure, however, may find some explicit directions useful.

[12] The data represent the growth of shortleaf and loblolly pine for the period 1935–39, in a tract of 1,004 acres in the Crossett Experimental Forest, Crossett, Ark.

TABLE 2.—*Stand-table-projection method of computing forecast of the per-acre growth of saw timber, assuming no deceleration* [1]

Step No. in computation	Computation of future stand, volume, and growth in volume										Total
1. Breast-high diameter class inches	6.0	8.0	10.0	12.0	14.0	16.0	18.0	20.0	22.0	24.0	------
2. Twice the bark thickness inches	1.2	1.4	1.6	1.7	1.9	2.0	2.2	2.5	2.8	3.2	------
3. Present d. i. b.[2] do	4.8	6.6	8.4	10.3	12.1	14.0	15.8	17.5	19.2	20.8	------
4. 5-year growth in d. i. b.[2] inches	.8	.9	.9	1.0	1.1	1.1	1.1	1.1	1.1	1.1	------
5. Past d. i. b.[2] (5 years ago) inches	4.0	5.7	7.5	9.3	11.0	12.9	14.7	16.4	18.1	19.7	------
6. Past d. o. b.[3] (5 years ago) inches	5.1	7.0	9.0	10.9	12.8	14.8	16.8	18.8	20.7	22.6	------
7. Growth in d. b. h. in 5 years inches	.9	1.0	1.0	1.1	1.2	1.2	1.2	1.2	1.3	1.4	------
8. Present average trees per acre number	26.3	14.9	11.6	10.2	6.7	4.0	1.9	.3	.3	.2	76.4
9. Expected survival in 5 years number	25.1	14.4	11.4	10.1	6.6	4.0	1.9	.3	.3	.2	------
10. Trees entering from two classes below number	0	0	0	0	0	0	0	0	0	0	------
11. Trees entering from class below number	------	11.3	7.2	5.7	5.6	4.0	2.4	1.1	.2	.2	------
12. Remaining trees do	13.8	7.2	5.7	4.5	2.6	1.6	.8	.1	.1	[4].2	------
13. Future stand (5 years hence) number	([5])	18.5	12.9	10.2	8.2	5.6	3.2	1.2	.3	.4	------
14. Future stock (5 years hence) board feet	------	------	580	938	1,263	1,271	986	486	156	252	5,932
15. Present stock do	------	------	522	938	1,032	908	585	122	156	126	4,389
16. Stock change or volume growth board feet	------	------	58	0	231	363	401	364	0	126	1,543
17. Annual growth in volume board feet	------	------	------	------	------	------	------	------	------	------	309

[1] For graphic steps refer to figure 3, where *A* is the source of data for line 2, *B* for line 4, *C* for line 6, and *D* for lines 8 and 9 above. Stand, mortality, and growth data are from the 20-percent inventory of September 1934, and the volumes in International ¼-inch rule are as given by J. W. Girard. *(17)*

[2] D. i. b.=diameter inside bark.

[3] D. o. b.=diameter outside bark.

[4] 0.1 tree expected to grow into next higher class was counted as remaining in this class.

[5] Lacking tree-movement data from the 4-inch class, no forecast is made for the 6-inch class. In fact, the premerchantable 6- and 8-inch classes are tabulated only to permit computation of total ingrowth for the 10-inch and larger classes.

First rule a sheet with 17 lines and 10 or more columns. Each line of the table provides space to record the results of one of the 17 steps in the computation.

Step 1. List 2-inch diameter classes from 6.0 inches up to the largest in the forest.

Step 2. Plot twice the bark thickness over diameter class (fig. 3-*A*), read values from curve to one decimal, and tabulate bark averages, as read from the curve, below the corresponding diameter class.

Step 3. Subtract bark averages (step 2) from each diameter class in order to estimate the average present diameter inside bark of each class.

Step 4. Plot average values for 5-year growth in diameter inside bark (twice the core measurements) over past diameter class (fig. 3-*B*), read curve, and list for each diameter class the average of wood growth inside the bark, as read from the curve.

Step 5. Subtract diameter inside bark growth (step 4) from estimated present diameter inside bark (step 3) to obtain diameter inside bark 5 years ago.

Step 6. For each diameter inside bark 5 years ago (step 5) read the corresponding diameter outside bark 5 years ago from a curve constructed by plotting each present diameter class (outside bark) over its present diameter inside bark (fig. 3-*C*).[13]

Step 7. Subtract the diameter 5 years ago (step 6) from the present diameter (step 1) to obtain the 5-year growth in diameter.

Step 8. List the average number of trees per acre in each diameter class (the stand table derived from data in field cruises, fig. 3-*D*).

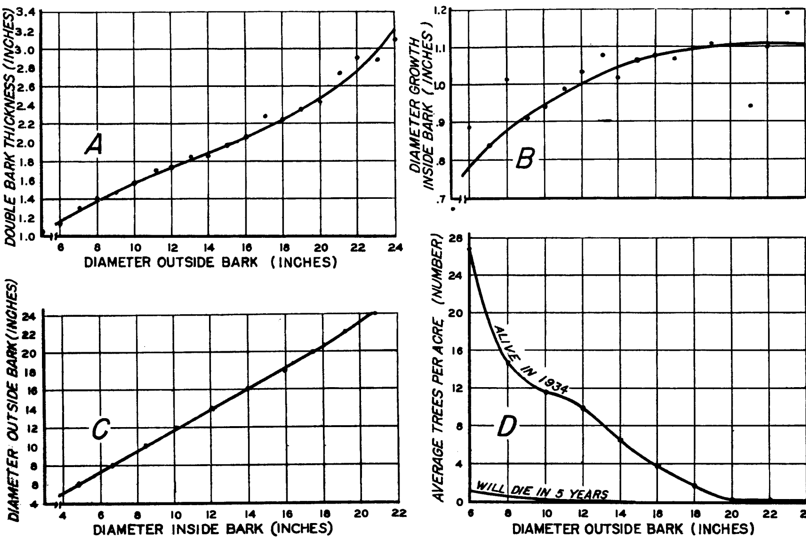

FIGURE 3.—Graphic steps used in stand-table projection to predict the future growth of merchantable timber from data gathered in a systematic inventory: *A*, Measurements of twice the bark thickness averaged by diameter classes (basis: 2,000 sample trees); *B*, average wood growth in diameter during 5 years (1930–34) from measurements of increment cores (basis: 2,000 sample trees); *C*, ratios of d. b. h. outside the bark to d. b. h. inside the bark (basis: 2,000 sample trees); *D*, present stand and mortality expected during 5 years, 1935–39 (basis: 20-percent cruise of September 1934).

Step 9. Subtract from the stand table (step 8) the estimated 5-year mortality (see lower curve fig. 3-*D*) to obtain the expected survival or basic stand for the forecast. (For convenience, and to facilitate checking, it would be advantageous to list this mortality on the work sheet between lines 8 and 9, before making the subtraction. Or, this deduction from the stand to allow for mortality (step 9) could be made after projection instead of before, that is, it could follow

[13] These data, being a combination of linear and curvilinear trends, naturally form a curve. They appear as a straight line in figure 3, *C* only because the vertical scale is too small to reveal the curvature. On work sheets the plotting scale should be large enough to permit listing results to one decimal, but if such a scale is inconvenient, then twice the bark thickness may be plotted against diameter inside bark and the readings added to the data in line 5 to obtain those in line 6 (table 2). Still another method to facilitate making the necessary allowance for bark, and to avoid the use of the curve (fig. 3, *C*), may be applied if the ratio between diameter outside bark and diameter inside bark is fairly constant for all diameter classes (i. e., if it can be plotted as a horizontal line). In this instance, the average ratio of diameter outside bark to diameter inside bark may be determined and applied uniformly to each diameter class to translate growth rates inside bark (line 4, table 3) directly into growth rates outside bark (line 7). Unfortunately, none of the methods here mentioned eliminates the possibility of error caused by a reversal of variables. (See discussion on p. 36.)

step 13 instead of step 8. For discussion of assumptions related to this choice, see page 13.

Step 10. Using the basic stand (step 9), the diameter growth rates (step 7), and the hypothesis of movement previously mentioned on page 15 (see also table 1), in discussing the second alternative in projection, record the number of trees, if any, expected to enter each class from two classes below during 5 years. (This happens when 1-inch diameter classes are used or when forecasts are made for longer periods.)

Step 11. Similarly record the number of trees expected to enter each class from one class below during 5 years.

Step 12. Subtract from the survival number in each diameter class (step 9), the number expected to grow out of that class (2 columns to right for step 10; 1 column to right for step 11) and record the remaining number of trees, or those not expected to grow enough in 5 years to emerge from their present class.

Step 13. The estimated stand after 5 years is obtained by adding together for each column the entries made in steps 10, 11, and 12.

Step 14. List future stocks, obtained by multiplying future stands (step 13) by figures from an appropriate volume table. (These figures, showing average volumes by diameter classes only, without any reference to heights or usable lengths, may be entered conveniently on the work sheet between lines 13 and 14.)

Step 15. In like manner list present stocks, obtained by multiplying present stands (step 8) by appropriate values from the same volume table.

Step 16. Stock change or estimated 5-year volume growth is listed by subtracting figures of step 15 from those of step 14.

Step 17. Divide the estimated total periodic volume growth (summation of step 16) by the number of years in the period, to obtain the final forecast of annual growth in volume per acre.

In projecting stand tables, some further considerations may arise, some of which are mentioned in the following discussion in order to clarify procedure.

Gathered on a timber cruise, the principal basic data here used to exemplify projection were those depicted (on a reduced scale) in figure 3 and in the table of tree volumes by diameter classes made by Girard, whose methods of constructing volume tables have been reported elsewhere.[14] This board-foot (International ¼-inch rule) table, combining loblolly and shortleaf pines, is not shown, as local tables are best used for this purpose.

As used in the present study, step 9, which lists the survival expected in 5 years, is merely the present stand minus an allowance for natural (5-year) mortality. The question arises as to whether the stand should not also be reduced to allow for the cutting of timber during the forecast period. No such reduction was made in this instance because the improvement cutting of the first period was largely confined to inferior trees unmerchantable as sawlogs, and hence not included in the stand-table figures. When, in accordance with present plans, selective cuttings are made continuously in the main stand, an

[14] See also footnote 9, p. 11. Another source of data useful in computing merchantable-timber volumes is a pocket-sized manual: HAWES, E. T., VOLUME TABLES, CONVERTING FACTORS AND OTHER INFORMATION APPLICABLE TO COMMERCIAL TIMBER IN THE SOUTH. Ed. 3, 45 pp. 1940. [Mimeographed.]

allowance for cutting as well as for mortality should be made in step 9, reducing the number of trees per acre in each diameter class by an amount that corresponds with current cutting practice. In projecting the future growth of stands that include timber to be cut progressively during a given period, it is convenient to assume either that all harvested trees will be removed at the middle of the period (and hence grow only half the time) or that only half the periodic cut will be present to grow throughout the period. When no cutting whatever is expected, it becomes imperative that deceleration of growth be estimated and allowed for in stand-table forecasts. This matter is discussed in more detail on page 31.

Having forecast future rates of periodic growth by diameter class, the stand expected to come through the period must be set forward. When applying the hypothesis of movement (option 2), illustrated in table 1, it is essential that the details of projection be understood. The simple way in which the figures are assembled to represent the future stand is not always apparent without specific illustration. Two or three examples from table 2 will serve to trace the derivation (from basic data in lines 1, 7, and 9) and tabulation (in lines 10 to 12) of projection figures totaled (in line 13) to represent the future stand. For instance in the 14-inch diameter class (column 5) the 6.6 trees (line 9) are expected to grow 1.2 inches (line 7). The movement factor, 1.2 times 50, equals 60 (table 1), and 60 percent of 6.6 trees equals 4.0 trees moving up and hence entered in line 11, one column to the right. Then 6.6 minus 4.0 leaves 2.6 trees remaining (line 12). Similarly, for the 22-inch class we have 0.3 tree expected to grow 1.3 inches; 1.3 times 50 or 65 percent of 0.3 indicates 0.2 tree moving up (enter in column to right for next higher class) and 0.1 tree remaining. All other diameter classes are treated in the same manner, except that 0.1 tree in the 24-inch class expected to grow into the next higher class (not tabulated) was conservatively counted as if remaining in the 24-inch class (line 12).

In forestry calculations using board feet, it is advisable to take into account the difference (often wide) between woods volume and mill output. Apart from personal and sampling errors, the discrepancy between estimated volume of timber or gross log scale, and "green-chain" or mill tally of sawn products is caused mainly by imperfection in three things: (1) The log rule as a device for measuring sound and perfectly formed logs, (2) the form and substance (soundness) of the logs measured, and (3) the workmanship of the sawyer at the mill. When the International ¼-inch kerf rule is used, and when logs are cut mostly into timbers at a large band mill, the first and third causes may be negligible. The effect of crook, rot, and other defects, however, remains to be considered. This may be estimated in scaling logs and approximated (as is done on some of the national forests) on the basis of the difference between gross and net scale. The introduction of selective logging is expected to cause first a temporary increase in cull percentage, as a result of improvement cuttings previously neglected, and later a permanent reduction in cull percentage as a result of early elimination of the most unsound and crooked trees. The precise determination of cull percentage requires the measurement of the contents of a typical lot of logs before and after milling. Unless the cull factor has been actually remeasured during a forecast period, it is recommended that the same percentage reduction of estimates of gross timber volumes, to allow for decay and other defects, be applied uniformly at the beginning and end of the period. Cull trees in merchantable size classes should be (and usually are) recorded separately by timber cruisers. Where this is not done, and where no deductions are made for defective portions of merchantable trees, a volume table based on sound and straight timber cannot be used without correction.

Simmons [15] suggests that this correction be made separately for each diameter class on the basis of information gathered from selected cruise lines used in check estimating. By this method, the percentage of trees observed to be unmerchantable for sawlogs in each class is plotted over diameter, and readings from the resultant curve are used to reduce the figures in the volume table. If necessary, preliminary or tentative estimates of cull percentage, cordwood volumes, etc., likewise may be based on observations restricted to certain plots or strips systematically selected and constituting a small but representative portion of the area cruised. The small plots often used to locate trees sampled for growth rates may be used to obtain such supplementary items of information as may be desired, e. g., cull percentage, age, merchantable height, and potential minor products.

If volume tables by diameter classes are already available for by-products, such as pulpwood or cordwood cut from tops of sawlog-size trees, a few extra lines in table 2 will adapt the stand-table method for use in predicting the yields of such minor products as well. Like the forecast of saw timber, this is based on the contrast between present and predicted stands shown in lines 9 and 13, so that only the last four steps in computation need be repeated. As previously pointed out, the matter of ingrowth from premerchantable classes, the calculation of which is an integral part of the stand-table method of forecasting growth, should not be neglected, as it may be a very large fraction of the total increment.

Example of Results Obtained by the Stand-Table-Projection Method

The second concept of growth movement (option 2) was applied in starting management of loblolly and shortleaf pine stands on the Crossett Experimental Forest in southern Arkansas. After a brief review of the results from the initial inventory and study of growth, the basic timber data from that project will be utilized again to illustrate the third concept—the one that attempts to measure dispersion in growth rates.

The map (pl. 1) based on a strip survey made in September 1934, shows forest subtypes and stand conditions in the usual detailed manner. Since about 680 acres of the 1,680-acre forest was reserved for intensive experiments, only the remainder was suitable for a demonstration of practical management. These 26 remaining "forties" constitute a 1,000-acre tract with over 5 million board feet of timber now placed under management for sustained yield.

The volumes of timber on this tract, as estimated in 1934, are shown in figure 4, by areas of the different types and conditions (*A*), and by

[15] SIMMONS, F. C. STANDARD R-7 COMPUTATION PROCEDURE, MANAGEMENT PLAN PREPARATION. U. S. Forest Serv., Region 7, 82 pp. 1938. [Mimeographed.]

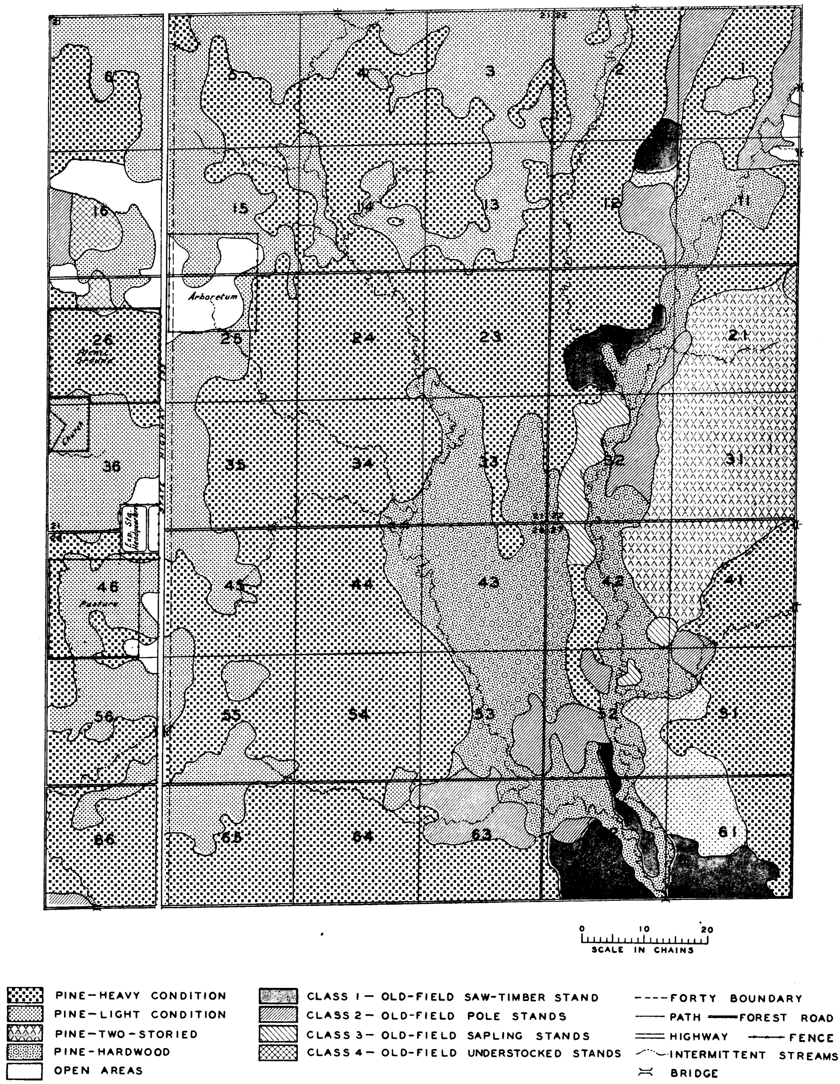

PLATE 1.—Map showing forest subtypes and stand conditions found on the Crossett Experimental Forest in the fall of 1934, when many of the growth data in this report were gathered as part of a 20-percent timber inventory. The volume of timber on 26 of these numbered 40-acre tracts is shown in figure 4, *B*. Estimates of growth appear in tables 2 and 4.

TABLE 3.—*Current annual growth of saw-timber stands (estimated on a 5-year basis) in board feet and in compound-interest rates, together with percentage of ingrowth, on cut-over land in southern Arkansas* [1]

ESTIMATED ANNUAL GROWTH PER ACRE

Species group	Natural pine stands				Old-field pine stands [2]			Average, all stand conditions
	Heavy	Light	Two-storied	With hardwoods	Nos. 1, 2, 3	No. 4 (open)	Total old-field	
	Board feet	*Board feet*	*Board feet*	*Board feet*	*Board feet*	*Board feet*	*Board feet*	*Board feet*
Loblolly pine	217	111	186	134	486	359	471	211
Shortleaf pine	92	104	106	21	85	6	75	82
Pines	309	215	292	155	571	365	546	293
Oaks [3]	13	7	25	51	5	2	5	18
Other hardwoods	16	6	12	37	8	14	9	17
Hardwoods	29	13	37	88	13	16	14	35
All species	338	228	329	243	584	381	560	328

COMPOUND RATES OF PERIODIC ANNUAL GROWTH

Species group	Heavy	Light	Two-storied	With hardwoods	Nos. 1, 2, 3	No. 4 (open)	Total old-field	Average, all stand conditions
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Loblolly pine	5.4	5.8	7.4	6.7	6.0	6.7	6.0	5.9
Shortleaf pine	6.0	8.8	12.4	5.6	5.7	3.5	5.7	6.7
Pines	5.6	8.7	8.7	6.5	5.9	6.7	6.0	6.1
Oaks	3.6	4.2	5.5	2.6	4.5	3.6	4.4	3.2
Other hardwoods	3.1	2.6	1.6	4.2	4.8	6.3	5.1	3.3
Hardwoods	3.3	3.3	3.0	3.0	4.6	5.7	4.8	3.2
All species	5.2	7.9	7.2	4.6	5.9	6.6	6.0	5.6

INGROWTH—PROPORTION OF TOTAL PERIODIC GROWTH [4]

Species group	Heavy	Light	Two-storied	With hardwoods	Nos. 1, 2, 3	No. 4 (open)	Total old-field	Average, all stand conditions
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Loblolly pine	12	7	31	11	23	22	--------	20
Shortleaf pine	29	23	41	24	41	28	--------	33
Pines	18	14	34	13	26	23	--------	23
Oaks	51	70	44	46	57	--------	--------	48
Other hardwoods	40	50	70	59	76	34	--------	56
Hardwoods	45	59	54	52	68	34	--------	52
All species	20	17	37	26	27	23	--------	26

[1] No allowance has been made for the inevitable deceleration of growth in those parts of the uncut forest where the crown canopy has closed. Whether or not these rates of growth can be maintained under judicious selective cutting remains to be seen.

[2] No. 1, sawlog-size stands; No. 2, pole-sized stands; No. 3, sapling stands; and No. 4, limby understocked stands.

[3] Red, white, and water oaks.

[4] Ingrowth data are for the entire 1,680-acre forest: other data are only for the 1,000-acre tract.

40-acre compartments (*B*). The upper blocks (hachured) represent the hardwood component of the stand, and include trees 13.5 inches d. b. h. and larger, while the lower unshaded blocks represent volumes of pines 9.5 inches d. b. h. and larger. The total estimate for the 1,000 acres was over 4 million board feet of pine and about 1 million of hardwoods (International ¼-inch rule); 29 percent of the pine timber and 69 percent of the hardwood timber was in trees 16.5 inches d. b. h. or larger. Considerable variation was found in average stands; the pine volume ranged roughly from 1,000 to 9,000 board feet per acre on the different forties (fig. 4, *B*), and averaged a little over 4,000.

The volume inventory also provided the basis for a growth study. It supplied nearly 400 hardwood and over 2,000 pine increment cores.[16] In analyzing growth-ring measurements from these samples,

[16] These cores were obtained by boring all sample trees found on 1,000 small plots taken at 2-chain intervals along the 20-percent cruise lines. For sawlog-size trees these plots were 1/40 acre (2.5 percent of the area) and for under-sawlog-size trees they were 1/160 acre (about 0.6 percent of the area). Hardwoods less than 8 inches d. b. h. and pines less than 4 inches were not sampled.

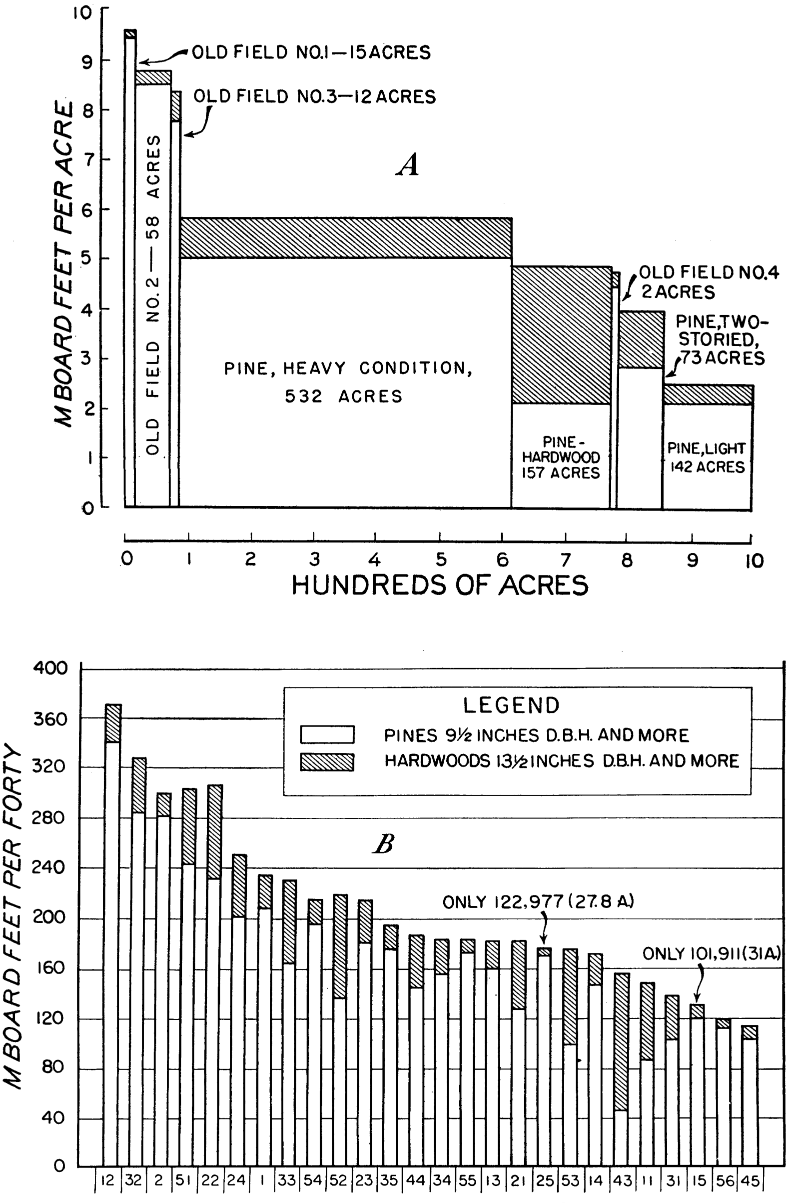

FIGURE 4.—Volumes of saw timber measured by the International ¼-inch kerf rule without making any deductions for defect, and portrayed by means of Wackerman's skyline graphs. These volumes were the growing stock on the 1,000-acre sustained-yield tract of the Crossett Experimental Forest, Ark., as determined by the initial 20-percent inventory of September 1934. *A*, By various stand-condition classes. The width of blocks indicates land areas; the height of blocks, the per-acre volumes; and the area of blocks, the total volumes. *B*, By 40-acre compartments numbered as indicated on the map, plate 1.

the apparent effect of crowding was noted, in that average diameter growth was invariably less during the last 5-year period than during the preceding 5-year period. Deceleration in the rate of basal-area growth on trees of sawlog size was found to be about 7 percent in 5 years. To be conservative in stating current growth, the slower growth rate for the past 5 years was used in preference to that of the past 10 years. Thus far no allowance has been made for further deceleration, however, because it is anticipated that it may be prevented by thinnings and improvement cuttings. The first cut of about 1½ cords of pine pulpwood and 3 cords of chemical hardwood per acre was taken almost exclusively from defective trees and widespreading branchy trees excluded from both the sawlog inventory and the initial determination of growth rates.

Current growth rates by species group and by type and condition of stand are given in table 3, which indicates that the annual periodic growth of pine during the immediate future will be nearly 300 board feet per acre, or at the compound-interest rate of 6.1 percent. Only 77 percent of this pine increment consists of enlargement of sawlog-size trees; the remainder is ingrowth, or the board-foot volume of trees that first reached sawlog size during the period. For hardwoods, ingrowth is half of the volume increment, and for the whole stand it is one-fourth of the increment. In young well-stocked second-growth stands the volume in new trees or ingrowth is often a considerable portion of the total increment. This abundance of ingrowth is confirmed by unpublished figures of the Nation-wide Forest Survey, which found that over extensive areas of sawlog-size second-growth forest in southwestern Arkansas about half of the hardwood and a third of the pine increment was ingrowth.

Growth Dispersion by Diameter Classes

Further refinement of the stand-table method requires a knowledge of the variation in rates of growth of individual trees (see third option for projecting stands, p. 16). By boring a large number of representative sample trees, timber cruisers can supply the necessary measurements. Enough samples of growth (increment cores) must be obtained to permit computation of the percentage of trees that remained in their initial diameter classes (e. g., as of 5 or 10 years ago) and the percentages that moved up one or more classes during the period. If sufficient samples are available, such information, worked out separately for each diameter class, should provide a much clearer picture of actual tree movements and theoretically should permit of more precise forecasts than the hypothesis of tree movement formerly described. This is especially true at present in many forests of southern pine, where the amount of ingrowth is exceptionally high, owing to the unusually large number of trees now just below the size limits used in stand forecasts. Under such conditions a special study of the dispersion of trees in the largest premerchantable size classes might be advisable where forecasts are needed.

The manner in which the arrangement of trees in diameter classes changes as a result of growth can be illustrated most effectively by a diagram. The grid constructed with arbitrary data and reproduced in figure 5 is not at all necessary in projecting stands by the dispersion method (as in table 4), but it has been found helpful in visualizing tree movements. Graduations on the horizontal scale indicate the initial size of each sample tree represented by a dot plotted directly above. Each dot is conceived as having started from the base line and moved (during 5 years) straight upward a definite distance, indicated on the vertical scale. The movement classes recognized in analyzing data from increment cores of sample trees are distinguished on the chart by the variously shaded areas. The diagonal bands, which represent diameter classes, as well as the

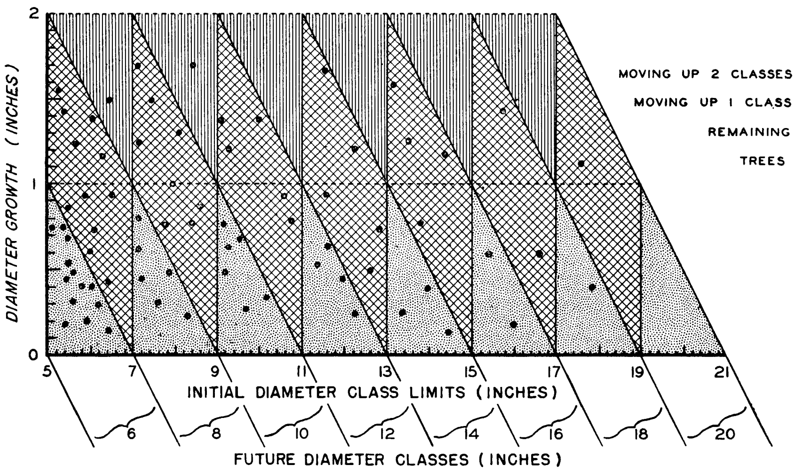

FIGURE 5.—Dispersion of growing trees by size classes. This diagram illustrates the manner in which both original position and variation in growth rate affect the final position of trees after a period of growth. Individual trees, represented by dots, are conceived as having started from points on the base line corresponding to their diameter when first measured, then having moved straight up a distance equal to their periodic growth on the vertical scale. In its new position as shown here, each dot shows two things about a tree: (1) Its advance in number of classes, indicated by the shaded background, and (2) its reclassification by diameter class for a new stand table representing conditions at the close of the growth period, indicated by position in a diagonal strip.

diagonal lines which delimit them, are needed to visualize the results of tree movements. The new classification of the trees after growing 5 years is indicated by the position of the dots as plotted. The diagram shows how the future distribution of trees in a stand is affected not only by individual variation in periodic diameter growth, but also by initial size or position of trees within the classes. For example, in diameter class 16 are two trees each of which grew 0.6 inch. While the larger tree entered the 18-inch class, the other one failed to emerge from the 16-inch class simply because it was smaller at the start. The manner in which trees are reclassified in diameter classes at the end of the period is shown by the diagonal bands. The total number of dots in each band (regardless of the shaded background) represents the reallocated trees for that diameter class.

TABLE 4.—*Stand-table-projection method, recognizing dispersion of rates of diameter growth within 2-inch diameter classes and assuming no deceleration* [1]

FIGURES USED TO COMPUTE FORECAST OF TIMBER INCREMENT

Step Nos. as in table 2	Figures used in a modified procedure for computing a forecast of timber increment, including ingrowth											Total
1. Diameter class ..... inches	6.0	8.0	10.0	12.0	14.0	16.0	18.0	20.0	22.0	24.0	26.0	----
9. Expected survival ..... number	25.1	14.4	11.4	10.1	6.6	4.0	1.9	.3	.3	.2	----	74.3
10. Trees from 2 classes below ..... do	----	----	.8	.3	.1	.1	----	----	----	----	----	----
11. Trees from 1 class below ..... do	----	11.5	8.2	5.4	5.2	3.7	1.9	.8	.2	.1	.1	----
12. Remaining trees ..... do	12.8	5.9	5.9	4.8	2.9	[2] 2.1	1.1	.1	.2	.1	----	----
13. Future stand ..... do	12.8	17.4	14.9	10.5	8.2	5.9	3.0	.9	.4	.2	.1	74.3
14. Future stock ..... board feet	----	----	670	966	1,263	1,339	924	364	208	126	74	5,934
15. Present stock ..... do	----	----	522	938	1,032	908	585	122	156	126	0	4,389
16. Volume growth ..... do	----	----	148	28	231	431	339	242	52	0	74	1,545
17. Annual growth ..... do	----	----	----	----	----	----	----	----	----	----	----	309
	BASIC DATA FOR THE ABOVE DISPERSION FIGURES											
Trees moving up 2 classes ..... percent	3	2	1	1	0	1	2	0	0	0	----	----
Trees moving up 1 class ..... do	46	57	47	51	56	48	39	56	50	33	----	----
Stationary trees ..... do	51	41	52	48	44	51	59	44	50	67	----	----
Total ..... do	100	100	100	100	100	100	100	100	100	100	----	----
Total cores ..... number	204	406	439	286	223	104	59	18	8	3	----	1,750

[1] The timber growth shown here was forecast for 1935–39 and represents an increase of 6.2 percent compounded annually.

[2] An actual loss of trees is recognized in a mortality allowance for the growth period (fig. 3, *D*), but a specious additional loss from rounding off to the nearest tenth in the above calculations is not tolerated. Nor does the possible slight gain in precision warrant retaining the second decimal place. Hence, in rounding off to the nearest tenth of a tree, the usual procedure is modified to permit the totals originally in each class (step 9) to be maintained throughout each dispersion estimate. For example, consider the disposition of the four 16-inch trees. With only 1 percent or 0.04 tree moving up 2 classes, the 20-inch class is not shown as receiving any of these trees. With 48 percent, or 1.92 tree, moving up one class, 1.9 tree is recognized as entering the 18-inch class. Similarly, 51 percent stationary trees indicates 2.04 trees remaining in the 16-inch class. But this last estimate is recorded as 2.1, not 2.0, to prevent the irrational loss of 0.1 tree through the cumulative effect of rounding off. The 0.1 tree could be arbitrarily included in any one of the three classes, but is conservatively counted with those that grew least.

A detailed calculation, utilizing data by 1-inch diameter classes and the simple hypothesis of tree movement (the second option described on p. 15) in the stand-table-projection method, estimated the annual increment of pine in relatively heavy (but still understocked) stands at 309 board feet per acre, of which 217 feet was loblolly pine (table 3). Dispersion of growth of loblolly pine computed from the same basic data indicated that during a 5-year period nearly 16 percent of the trees did not grow enough to emerge from their initial class, 67 percent entered the next class above, another 16 percent moved up two classes, and only about 1 percent moved into the third class above.

Applying these percentage movements (16, 67, 16, and 1 percent) to each diameter class in place of the simple hypothesis of tree movement as first applied, gave an estimate of 178 board feet of growth, 39 feet (or 18 percent) less than the first detailed estimate. An underestimate was to be expected because the application of identical percentage movements, of 0, 1, 2, and 3 classes to all diameters, assumes that average rates of growth are equal for the various diameter classes. Figure 3, *B* shows that the rates are not equal. Calculation on this erroneous assumption undervalues the larger trees, which are not only growing faster in diameter, but for which a given amount of diameter growth means a greater volume growth. The soundness of applying percentage movements derived from sampling the whole stand to individual diameter classes seemed questionable. Accordingly, dispersion was computed separately for each class. On this basis, the forecast was somewhat improved, the result being 193 board feet, 24 feet (or 11 percent) less than the original figure. An apparent explanation of the remaining discrepancy lies in the possibility that the sampling was not sufficiently intensive to make the dispersion data valid by separate 1-inch classes and for loblolly alone (see section on diameter-class intervals, p. 36).

Similar observations were then made on the dispersion of growth rates by 2-inch diameter classes, except that shortleaf was included with the loblolly in these calculations. In these larger classes, 48 percent of the pines remained for 5 years in their initial class, 51 percent moved up one class, and 1 percent moved up two classes. Projecting each diameter class 5 years into the future on this basis yielded a growth estimate for both species of 304 board feet. If the 92 board feet of shortleaf pine growth shown in table 3 be subtracted, the result is 212 board feet of loblolly pine growth, which is 5 board feet (or 2.3 percent) less than the original estimate. Dispersion computed separately by 2-inch diameter classes was then applied, as illustrated in table 4. The result in annual per-acre growth was then 309 board feet of pine. Subtracting 92 board feet of shortleaf, as before, leaves 217 board feet of loblolly pine growth. This is identical with the original estimate based on 1-inch classes and the simple arbitrary hypothesis of tree movement. Apparently, then, very similar results may sometimes be obtained by using either the second or the third option in projecting stands. Where dispersions in growth rate within diameter classes are very similar to the average dispersion for the stand, the result using the second option should closely approach that using the third option. The identical results in one instance, however, are regarded as a mere coincidence, as exact agreement cannot be expected from these various procedures.

From the present study it appears that although a method of stand projection which recognizes dispersion of growth is clearly preferable where a study of the distribution of trees by size classes is desired, its results seem to correspond closely with those of the simpler optional methods of estimating the net volume growth of stands on the basis of average rates of diameter growth. In fact, when growth in volume alone is sought, and when abundant borings are available to insure an adequate sample not weakened by subdivision, there may be very little difference in the accuracy resulting from any one of the three projection procedures already described.

Avoiding Unnecessary Detail

Since the degree of intensity and refinement required in estimating timber growth was entirely unknown when this study was started, the results from very detailed initial computations were used as a yardstick in judging the extent to which similar recomputations of the same data by the same method could be abbreviated safely. While this was no test of the value of the method selected, it did show, at least in this instance, how considerable unnecessary clerical work could be avoided without any apparent loss in accuracy.

The long procedure, which utilized a maximum subdivision of samples of basic data (stand tables and core measurements), was aimed at detailed results. Separate forecasts (24 in all) were made for each of the stand conditions and species groups indicated in table 3. Separate curves of bark thickness, growth, and stands were made for each forecast, and a 20-step computation carried to the second decimal place was applied to each 1-inch diameter class.[17] Final results of this computation are shown in table 5. The cost of computing this detailed information seemed entirely unwarranted from a management standpoint, if the same figure, an annual growth of about 328 board feet of all species per acre, could be obtained by shorter methods.

TABLE 5.—*Effect of abbreviating procedure in predicting annual increment per acre of timber by the stand-table-projection method*

Species groups	Component forecasts utilized (number)			
	24	8	3	2
	Board feet	*Board feet*	*Board feet*	*Board feet*
Loblolly pine	211	216		
Shortleaf pine	82	80		
Pines	293	296	295	319
Oaks	18	17		
Other hardwoods	17	18		
Hardwoods	35	35	33	33
All species	328	331	328	352

To simplify procedure the first step was to combine the data for all types and conditions except for the open-grown old field (No. 4), which required the use of a separate volume table. All other refinements in method were temporarily retained, but only 8 separate forecasts were made, thus eliminating about two-thirds of the work. The result indicated a growth of 331 board feet per acre per year; since this was within 3 feet of the previous figure, it was deemed entirely satisfactory.

The next economy was to handle all hardwood species in one group [18] and combine the data for the two species of pines. The open-grown old field remained segregated as before, but as this old field contained no merchantable hardwoods, the total number of forecasts was reduced to 3, thus eliminating seven-eighths of the original numerical work. Calculations were shortened still more by handling all data by a 2-inch, instead of a 1-inch, diameter-class interval, and carrying only one instead of two decimal places. Furthermore, three of the least essential steps in computation were eliminated from the original 20-step procedure. All short cuts combined gave a final net result of 328 board

[17] These 20 steps were identical with the 17 steps as earlier specified and illustrated in table 2, except that they included 3 additional steps later discarded as unnecessary refinements.

[18] The saw-timber hardwoods as a group, which are associated individually with pines throughout the tract, showed no relation between growth rate and size, but with an average diameter growth of 0.7 inch in 5 years, they were numerous enough to contribute 35 board feet to the annual growth per acre.

feet per acre per year—the same as that derived by the original complicated procedure. Of course, this complete agreement is merely coincidental, for table 5 indicates that an overrun of 2 board feet in the pine estimate happened to be offset exactly by a similar underrun in the hardwood estimate.

In predicting growth by these methods a simple and satisfactory form of computation is the one illustrated in table 2.

The next trial attempted to combine data for the natural second-growth pines with those for the open old-field pines that occupied only 1 percent of the total area. A slight adjustment weighted by numbers of trees was made in the volume table to make it theoretically applicable to all pine timber. This adjustment apparently was incorrect, however, as it failed in its purpose. The combined result from the one hardwood and one pine forecast (table 5, last column) gave an overestimate of 24 board feet (about 7 percent) and saved little time. When volume tables known to apply closely to certain parts of a forest show wide differences in volume for trees of given diameters, they are best used separately, as any casual attempt to combine them may simplify predictions of growth only at the sacrifice of desired accuracy. The volume tables for pine and hardwood were so different that their possible combination in approximations was not attempted. Apparently the point of rapidly diminishing returns from eliminating details had been reached.

Deceleration or Acceleration—A Source of Error

In using any variation of the stand-table-projection method, a fair degree of accuracy, of course, can be attained more easily in a short-time prediction, but even in short forecasts it is manifestly unsafe to rely blindly on the assumption that the trees will grow in the near future exactly as they did in the recent past. Clearly some attention should be paid to the current trends in growth rate. It is true that where climatic or weather changes are significant in the changing rate, accurate forecasts of growth may be impossible until the major climatic changes, such as marked variations in precipitation during the season of active growth, can be predicted satisfactorily for a reasonable period of years in advance. Nevertheless, even where the weather is not expected to have a significant effect, the ever-present influence of constantly changing density in the forest should not be overlooked.

To gage the effect on forecasts of neglecting natural deceleration of growth, a 10-year record of the actual growth of all trees on certain permanent plots was utilized. The data were for young, even-aged, well-stocked stands of longleaf pine in southern Mississippi. The stands expected after 5 years were forecast by each of the three optional variations of the stand-table-projection method (see pp. 15–17), and results were compared with the actual behavior as recorded from complete field measurements. The differences between the net results of the three variations in projection were slight, but all three methods showed very large positive errors. In predicting cubic volume in standing trees per acre the overrun was 31 to 33 percent. The errors in the accompanying estimates of growth in volume were even more startling—78 to 84 percent, respectively! When the observed retardation of growth was taken into account, by correcting past growth previous to projection, the predictions all corresponded closely with the records of actual growth on these plots. For example, using the first and simplest option in projection, the error in prediction was reduced from 78.5 to 3.6 percent. Apparently the failure to allow for deceleration of growth in well-stocked stands that are not scheduled for thinning is the underlying cause of inordinately large errors in forecasts.

In a managed forest, on the other hand, the loss of increment in timber volumes resulting from both mortality and deceleration of diameter growth in uncut portions of the forest is sometimes vaguely assumed to be offset by accelerated growth following the selective cutting of other portions. It would be preferable, where possible, to determine by special study what changes in growth rates it is reasonable to expect. In understocked forests or parts of forests, the rate of diameter growth of many individual trees may remain fairly constant whether the stand is cut over or not, simply because for these trees there is temporarily enough space to permit nearly the maximum rate of growth in either event. As indicated in denser forests, however, particularly in those consisting of even-aged stands, the future growth of trees on the partly cut areas may be much greater than that on uncut tracts. In planning for the regulation of future cuts, the average increment by the stand-table-projection method should be determined (table 2) only after correcting observed rates of growth to make some sort of allowance for expected changes. Such an allowance may be based on recent deceleration in average diameter growth, as measured on cores obtained in timber cruising. Although the most dominant trees may maintain rapid diameter growth throughout life, the growth of the subdominant and medium-sized trees in a stand often slows down. Growth retardation in the average tree may be used to approximate that of the stand as a whole. Accepting as inevitable a certain decrease in average diameter growth as measured in inches, we may set up a constant growth in basal area (*23*) as a basis for measuring excessive retardation of diameter growth. Working with ponderosa pine, Baker (*3*) has shown that actual diameter growth and diameter growth computed from a constant basal-area increment are very much the same. This tendency, which is the natural result of distributing approximately the same amount of wood over a larger surface each year, held for both slow-growing and rapid-growing trees. (An illustration of reduced ring width under constant basal-area growth is given in the second paragraph on p. 8.) Thus, only a reduced rate of growth in basal area need be regarded as a reduction in stand growth. On this basis expected deceleration may be roughly approximated from the basal areas of successive average diameters. For example, on the experimental forest the diameter (at breast height) of the loblolly pine of average basal area (including only trees 3 inches and larger in 1934) changed from 8.7 inches 10 years earlier (1924) to 10.1 inches 5 years earlier (1929), and reached 11.2 inches at the time of the survey (1934). Basal areas corresponding to these average diameters are 0.4128, 0.5564, and 0.6842 square foot, respectively. For constant growth in basal area (no excessive deceleration in d. b. h. growth), the present basal area may be forecast from the above figures as follows:

0.5564–0.4128=0.1436 square foot (growth in first half of past decade)
0.5564+0.1436=0.7000 square foot (theoretical present basal area).

This theoretical basal area corresponds to a diameter of 11.33 inches instead of the actual 11.20 inches. The difference, 0.13 inch (or about 9 percent of the actual diameter growth, 1.4 inches during the first half decade) may be regarded as the amount of deceleration in current diameter growth for this stand during the second half of the past decade. Thus deceleration may be defined as the amount of retardation in average diameter growth that is in excess of that expected on the assumption of constant increases in basal area. Little confidence can be placed, however, in such a figure (9 percent) derived from such an oversimplified procedure. It may be advisable to investigate the deceleration more thoroughly, estimating it separately by diameter classes.

The trend of deceleration is recognized in this manner in table 6, in which the results of projection of reduced growth by diameter classes are compared with actual measurements of the same stand. Instead of depending on a blanket reduction of growth, the diameter classes were treated as suggested by Chapman (*10, pp. 361 ff.*), and the resultant percentage corrections are shown in line 3 of table 6. The result was a positive error in the volume of stocks, and in the growth forecast, of 15.6 cubic feet per acre; this error was equivalent to 4.6 percent of the growth volume and 1.8 percent of the stand volume. Chapman's method requires that past radial growth for two or more 5-year periods be measured separately. To show the trend for each diameter class, a separate curve is drawn. For young, uncut stands the increasing effects of competition are indicated by curves (of diameter over years in the period) that are concave downward. As such curves show recent deceleration of growth, they can be extrapolated to forecast further retardation expected during the immediate future of the same stand. It may be advisable first to harmonize the series of curves so that the general trend reflects the approximate form of the stronger curves. The trend of each is then extended to cover the forecast period, and an estimate is read off for each diameter class.

Thus deceleration estimated directly by curvilinear projection, in which growth in small trees was reduced more sharply than in larger trees, served to bring the prediction of volume growth per acre within reasonable limits of accuracy. It is doubtful if straight-line projection should ever be used.

In forecasting timber increment, it would seem that any change in rate of growth could be handled by identical procedures. Growth accelerated as a result of increased growing space is simply the reverse of the decelerated growth in crowded stands. One difference, however, is noteworthy. The typical effect of crowding is gradual deceleration easily portrayed by curves, whereas the effect of release is often abrupt—not following any trend discernible in the past history of the same stand. This contrast naturally will be less evident in stands cut lightly at frequent intervals than in those cut heavily at longer intervals. In the past, because of common practice of heavy cutting, it has been necessary to make specific studies of accelerated growth. Trees of different species, age, and development vary in their ability to withstand crowding and later to recuperate. Hence local information on the possibilities of increased growth by tree classes and species is useful in forecast work, to the

TABLE 6.—*Stand-table-projection method, recognizing deceleration in rates of growth, by 1-inch diameter classes, and comparing results of forecast with measurements of the actual stand on permanent sample plots* [1]

Step No. in computation	Projection of reduced growth and comparison with actual measurement of the same stand											Total
1. Present diameter class (1933) inches	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	-----
2. Diameter growth 1929–33 inclusive inches	1.0	1.4	1.7	1.8	1.9	1.9	1.8	1.5	(1.1)	(0.7)	-----	-----
3. Deceleration-reduction factor percent	30.0	48.0	57.5	61.0	63.0	64.0	64.5	65.0	65.0	65.0	65.0	-----
4. Reduced growth expected inches	.3	.7	1.0	1.1	1.2	1.2	1.2	1.0	.7	.5	-----	-----
5. Trees per acre in 1933 number	131.5	119.0	80.5	50.5	50.5	33.0	16.0	12.5	2.5	1.0	0	-----
6. Survival after 5 years (1938) number	93.0	115.0	80.5	50.5	50.5	33.0	16.0	12.5	2.5	1.0	0	-----
7. Entering from 2 classes below number	-----	-----	0	0	0	5.0	10.1	6.6	3.2	0	0	-----
8. Entering from 1 class below number	-----	27.9	80.5	80.5	45.5	40.4	26.4	12.8	12.5	1.7	.5	-----
9. Remaining in original class number	65.1	34.5	0	0	0	0	0	0	.8	.5	-----	-----
10. Estimated future stand (1938) number	-----	-----	80.5	80.5	45.5	45.4	36.5	19.4	16.5	2.2	.5	-----
11. Actual future stand (1938) number	-----	-----	82.0	56.5	46.0	45.0	31.5	21.5	14.5	5.5	1.0	-----
12. Error in stand forecast number	-----	-----	−1.5	24.0	−.5	.4	5.0	−2.1	2.0	−3.3	−.5	-----
13. Volume per tree (volume table) cubic feet	-----	-----	.7	1.1	2.1	3.7	5.3	6.8	8.3	10.0	12.0	-----
14. Estimated future stock (1938) cubic feet	-----	-----	56.4	88.6	95.6	168.0	193.4	131.9	137.0	22.0	6.0	898.9
15. Actual future stock (1938) cubic feet	-----	-----	57.4	62.2	96.6	166.5	167.0	146.2	120.4	55.0	12.0	883.3
16. Error in stock forecast cubic feet	-----	-----	−1.0	26.4	−1.0	1.5	26.4	−14.3	16.6	−33.0	−6.0	+15.6
17. Percentage error in volume percent	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	+1.8
18. Actual present stock (1933) cubic feet	-----	-----	56.4	55.6	106.0	122.1	84.8	85.0	20.8	10.0	0	-----
19. Estimated growth 1933–38 cubic feet	-----	-----	0	33.0	−10.4	45.9	108.6	46.9	116.2	12.0	6.0	358.2
20. Actual growth 1933–38 cubic feet	-----	-----	1.0	6.6	−9.4	44.4	82.2	61.2	99.6	45.0	12.0	342.6
21. Error in growth estimate cubic feet	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	+15.6
22. Percentage error in growth percent	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	+4.6

[1] Data are from even-aged longleaf pine stands in southern Mississippi. Values in parentheses in line 2 were obtained by extrapolation. Values in line 3 were read from a balanced curve. Stand and mortality data (lines 5, 6, and 11) are from sample-plot records. Volumes in line 13 were adapted from Miscellaneous Publication No. 50, U. S. D. A. (1929). Stand projection was made according to the hypothesis of tree movement (see discussion of second option in projection). All figures are on a per-acre basis.

extent that such classes and species have been recognized in timber cruising.

A report by Barrett (*4*) on longleaf pine is a case in point. In 1927 a study of accelerated growth was made at Urania, La., on an area logged in 1904, where fires were uncontrolled until 1916. The original virgin stand of 90 to 100 trees per acre had been cut so that 12 unmerchantable trees per acre remained. Pronounced release was noted in four size classes. The first 2 classes, covering trees 6 to 9 inches d. b. h. at the time of logging, produced approximately 6 times as many board feet of lumber during the 20-year interval after logging as they did during an equal period of time before logging. The 10- to 11-inch class produced slightly over 5 times as much after logging as before. The largest group, 12- to 14-inch trees, increased in growth only a little over twice as fast after logging as before. Unlike the smaller ones, these larger trees were not seriously suppressed in the original stand. In studying accelerated growth, an obvious need is some sort of classification of trees that will segregate these different responses to release.

Another example is afforded by a relatively more shade-enduring species of southern pine. Chapman (*9*) has reported the remarkable recovery and growth of loblolly pine following suppression. MacKinney (*29*) studied increased growth in loblolly pines left after partial cutting, using a constant growth in basal area as the standard for determining changes in growth rate.[19] Mean annual growth in basal area for a 5-year period before release was taken as the equivalent of growth that would have been made in an equal succeeding period if the trees had not been released from competition. Increment exceeding this amount was regarded as accelerated growth. An inverse linear relation was observed between basal area and increases in basal-area growth. Crown development as indicated by crown width and crown ratio (length of crown as percentage of tree height), had most influence on growth. To utilize this information in predicting the sizes of individual loblolly pine trees 10 years after release, the following formula was presented: 0.8681 basal area (including bark) at time of release + 0.2914 crown ratio + 0.0065 crown width + 1.6332 basal-area growth during the 5 years before release + 0.0017 total height − 0.1212 equals basal area (including bark) 10 years after release. Standard error of estimate equals 0.0613 square foot. Only slightly larger standard errors (about 0.07 square foot) were expected in the use of two simpler formulas. As predicting mechanisms these were presented by MacKinney in the more readily usable form of alinement charts. On the average, the basal-area growth at breast height of loblolly pine trees released by cutting to a flexible 10-inch diameter limit was found to be 130 percent greater in the 10 years following cutting than the growth expected without release.

Obviously the neglect of deceleration in uncut stands or of acceleration in heavily cut stands can be a source of large error and may easily make a growth forecast utterly unreliable. In predicting the future volume of forest stands, a suitable allowance for probable changes in the average rates of growth seems more important than the choice of a detailed projection procedure.

Other Possible Sources of Error

When a volume table is used in the process of estimating growth, it is obvious that the table employed should not be changed in the course of any one estimate. Nevertheless, many timber-volume tables are based on changing commercial limits of utilization and hence may badly need revision from time to time. Also the character of the trees in the forest may change, so that the height, form, and volume typical of a diameter class may be very different at the end of the forecast period from those at the beginning. Thus shifts in both

[19] See pages 4 and 32 of this bulletin and references (*3*) and (*23*).

the degree of utilization and the dimensions of trees cause ordinary board-foot volume tables to be a source of error in growth forecasts.

Error may result also from the unwarranted conclusion in step 2 that the sweeping **S**-shape of curve *A* in figure 3 is typical. The inflection in this curve and its concave upper portion are traceable in this instance to the loblolly pines, particularly those growing in two-storied stands. The inflection was not characteristic of loblolly in all stands, nor of any shortleaf pine. Possibly the bark thickness of other second-growth stands may be shown best by some other type of curve. For this reason, and, as will be shown later, because bark-thickness curve *A* is the basis for curve *C*, the curve *A* should be constructed very carefully.

Another possible source of error is inherent in step 6 and curve *C* (fig. 3). This involves a reversal of the dependent and independent variables in plotting and reading curve *C*, which shows the ratio of the diameter inside bark to the diameter outside bark. Bruce (*8*) has cautioned foresters against the pitfalls from this particular misuse of curves. Only the values of the dependent variable can be read safely from most curves. It would seem that inaccuracy in the tilt or slope of a curve constructed by minimizing the residuals of plotted points along the abscissae only, may cause error when readings are made on the ordinates, or vice versa; but to limit the use of curve *C* to the reading of items plotted originally as the dependent variable would destroy its usefulness in the present procedure. One way that has been suggested to reduce this difficulty again refers to the method of locating the basic bark-thickness curve *A*; it requires that the selection of samples be purely random and not in any way influenced by either variable. In step 2, if instead of relying solely on averages by diameter classes, the individual measurements were plotted, residuals measured at right angles to the general direction of the curve, and the curve located (balanced-in) by minimizing these residuals in a trial-and-error location process, then the inaccuracy resulting from reversal of variables in making and reading curve *C* should be less. Some inaccuracy still remains, however, so long as common errors in measurement of bark thickness (used in estimating diameter inside bark) and the usual errors in measuring diameter outside bark are not represented by comparable scales in figure 3.[20] The magnitude of discrepancies resulting from plotting only the average bark-thickness figures, and thus neglecting the above precaution, was not measured in the present study.

Diameter-Class Intervals

In shortening the calculations used in the study of growth, the change from 1-inch to 2-inch diameter classes eliminated much work. The economy is realized largely in the office rather than in the forest, as numerous classes can be recorded on field sheets with little extra effort. The larger classes are better for extensive inventories and general studies of forest stands, since much information can be portrayed and used just as well by large classes as by small ones.

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[20] Deming, W. Edwards. some notes on least squares. U. S. Dept. Agr. Graduate School, i–181, illus. 1938. [Mimeographed.]

For certain special purposes, however, a 1-inch interval may be more advantageous; the handling of guiding diameter limits in selective cutting is an example. Fortunately, where strong stand curves have been constructed by large classes, the stand data can be reallocated to small classes by the method shown in the second paragraph below. The situations in which forest stand data can be handled better throughout in 1-inch classes are in general those involving data limited by factors other than the degree of sampling. Three examples of this may be given: (1) Where the range of saw-timber sizes is small, e. g., from 12 to 18 inches d. b. h., a common condition in second-growth pine timber; (2) where the area unit of forest regulation is small, e. g., 40 acres or less; and (3), where the total volume of material is small, as in many farm woodlots. Even when growth borings are available in abundance 1-inch classes are sometimes preferable; for example, when detailed information on growth dispersion is sought, it surely can be reflected most clearly by using 1-inch diameter classes.

On the other hand, deficiencies in the degree of sampling of abundant material may not be discovered until the field work has been completed, and yet some information on dispersion may be desired. In this situation the 2-inch classes are preferable because they avoid too much subdivision of scanty data. It should be understood that, for a reliable determination of average growth, a true measure of dispersion requires much more thorough sampling. In most situations, it is believed that stand data can be handled satisfactorily in the 2-inch classes in which they were recorded, or in the 1-inch classes derived directly from them.

A simple graphic method of converting stand data from one diameter-class interval to another is illustrated in figure 6, *A*. In converting from 2- to 1-inch diameter classes, or vice versa, there are only four essential steps: (1) Culminate frequencies from large to small diameters so that the stand table shows the average numbers of trees per acre in and above each diameter class; (2) plot these frequencies, not over the midpoint of the range in each class which may appear on the abscissae, but rather over the lower limits of the class interval used, and draw a smooth balanced curve; (3) determine accumulated frequencies according to the new class interval by reading the curve at lower limits of the new class interval; and (4) beginning with the largest diameter class, subtract each frequency from that shown for the next smaller diameter class. This results in a stand table of absolute number of trees per acre according to the new interval. Figure 6, *B* illustrates the result of using a different class interval to show the same present and predicted stands.

RECURRING-INVENTORY METHOD

This method, otherwise known as the continuous forest-inventory system or "methode du controle" was originated in France by Gurnaud (*19*, *20*, *21*) as early as 1878. He reported it to be "primarily a principle of order" resulting from simple, easily verified measurements of trees. The method apparently received but scant attention, however, until the following century, when it was revived, interpreted, and applied in Switzerland by Biolley (*5*, *6*) who referred to it as the "cardinal operation of management." Recently the method has been advocated for the United States by Kirkland (*27*), and some of the simple forms in which growth records may be handled under this system have been clearly illustrated by Meyer (*30*).

Strictly speaking, the "method of control" is not a device for forecasting future growth but rather a convenient means of determining past growth of forests that are managed silviculturally under a system of regular partial cuttings for harvesting timber. When these have become stabilized over a considerable period, the prediction of future yields is facilitated, because it rests simply on the confident expectation of continuing, with but minor variation, the yields realized in the past.

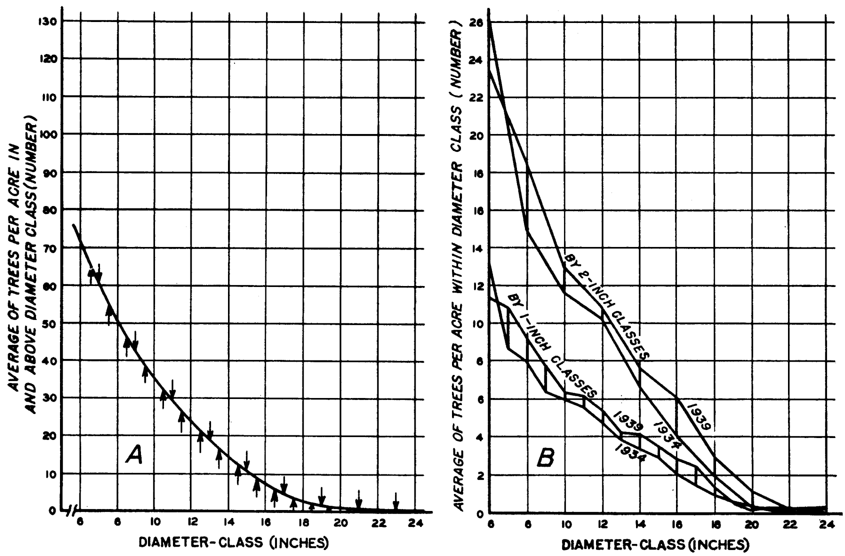

FIGURE 6.—Differences in the average number of trees per acre as a result of recording them by 1-inch and 2-inch class intervals are illustrated here. *A*, A method of using a cumulative frequency curve to translate a stand table based on a 2-inch interval to read in equivalent accumulated 1-inch diameter classes, or vice versa. The curve must be plotted over the lower limits of each class by the old interval (see arrows over curve) and read from the lower limits of each class by the new interval (see arrows under curve). Midpoints of alternate 1-inch classes and of each 2-inch class are shown on the horizontal scale. *B*, Estimated changes in the pine stand in 5 years as portrayed by 2-inch classes are contrasted with the same changes as portrayed by 1-inch classes.

The concept of repeated inventories is not entirely new in America, where it has long been recognized as the accepted procedure in studying timber growth on permanent sample plots. It is the method of regulation used on many of the Swedish forest estates. Regarding this system, the literature (mostly European) deals with two aspects: (1) The procedure and possible errors in determining growth, regulating the cut, and keeping records, and (2) the kind of forestry with which such management is most compatible, specifically the types of forest and systems of silviculture which best lend themselves to this kind of control.

Although the first aspect is of primary interest in the present report, the second also deserves some attention. In pointing the way to American application of the continuous-inventory flexible rotation system, both aspects of the problem are recognized by Kirkland (*27*) who has suggested the procedures, inventories, and records needed for properly allocating and regulating the cut by compartments or other management units. He has also stressed the need for paying attention to the quality of wood produced; in other words, for seriously considering the value as well as the volume of growth. Certainly the advantages afforded by this new approach should be welcomed by every American forester who is at all familiar with the unsatisfactory past history of growth prediction in general and of attempts to apply normal yield tables in particular. The practical application of yield tables has been especially difficult because actual stands, approaching a remote normal at various indefinite rates, fail to remain in their initial classification in respect to the yield tables. On the other hand, the recurring-inventory system provides a means of determining current increment in volume, basal area, or diameter by diameter classes, and can be applied by sample plots, strips, whole stands, or forests. Because of its speed and relative cheapness, it appears best suited to large areas. Recurring inventories of timber on each working circle would place the regulation of American forests on a firmer foundation.

UNDERLYING THEORY AND DETAILED PROCEDURE

It will be recalled that several variations of the stand-table method of forecasting (as previously described) utilized growth and mortality data by diameter classes to predict changes in stands. The continuous-inventory system reverses this approach to a knowledge of growth. Periodic changes in stands and mortality are the items that are measured directly, and from summaries of these tallies the growth behavior of individual diameter classes may be deduced if desired. The basic concept on which growth determinations rest in this inventory system is very simple. Covering a given period, e. g., 5 or 10 years, trees that died are added to a stand table of living trees harvested and both are added to the stand of living trees inventoried at the close of the period. The difference between this total and the stand at the first inventory is the gross periodic growth.

The procedure given by Meyer for tabulating this information may be outlined briefly. Tabulate (by diameter classes) in eight columns as follows:

1. Diameter class.
2. Number of trees at first inventory.
3. Number of trees at second inventory.
4. Number of trees removed during the period.
5. Number of trees at second inventory, plus those removed—(3) + (4).
6. Number of trees at second inventory, plus those removed and minus the number at the first inventory—(5) − (2).
7. Number of cubic feet (or board feet) per tree from volume table.
8. Cubic-foot (or board-foot) increment per diameter class—(6) × (7).

Except for Nos. 1 and 7 all columns are totaled, and plus or minus signs must be observed for the algebraic sums. This net growth (including ingrowth, which is the total of column 5 minus total of column 2), thus can be recomputed directly and easily whenever necessary from successive inventories of a timber-growing property. These repeated revisions supply current information vitally needed in the practical regulation of forests for sustained yields.

The basic inventories may be subjected to further analysis when growth rates by diameter classes are desired, and if the none-too-accurate hypothesis of tree movement (p. 15) is acceptable. As this method is set up in detail by Meyer, it is readily seen to be just the reverse of the procedure illustrated in table 1 of the present report. In deriving rates of growth by diameter classes from stand data, Meyer uses a factor that he calls "double rising over double effective." For each class this factor is a different ratio, with the numerator the sum of the trees entering and emerging from each class, and the denominator the sum of the numbers shown by the first and second inventories of the class. The decimal expression of these ratios may be seen to correspond with the percentage figures listed in table 1 as movement factors, indicating the reliance of the two methods on the same hypothesis of tree movement. The weakness of this hypothesis and the false assumptions on which it rests have been discussed already; they were called to Meyer's attention by Kakasai (*26*), who concluded that the method is inapplicable. Computations by Meyer (*31*) indicate that the errors are not large. Unless serious error can be traced to this method and until some simple alternative of superior accuracy appears, practical application should not be discouraged. When growth rates by diameter classes are dispensed with, reliance on the questionable hypothesis of movement is circumvented, and recurring inventories certainly supply a very practical means of determining volume increments under continuous forest management.

For the present, however, the possibility of deriving figures for periodic diameter growth by diameter classes indirectly through an analysis of changes in stand tables is of interest. If this indirect method were found to be reliable, it might make boring sample trees unnecessary. For the example used repeatedly in this report, the second inventory is not available, and so the results of applying this method cannot be compared directly with those of previous calculations. Nevertheless, if the previously predicted stand plus mortality be used to represent the second inventory, an illustration of the inventory method may be set up so as to obtain growth averages to compare with the results of actual boring. This has been done in table 7, with data from table 2 tabulated here to show the computation process reported by Meyer (*30*). The figures listed under "second count" should always be the stand table from the second timber cruise, plus all trees that died or were cut since the first cruise. The diameter classes are listed in descending order so that the detailed computations may proceed logically.

In the 26-inch class an average of 0.1 tree per acre appeared at the second count and none at the first count. Enter this 0.1 tree as growing out of the 24-inch class (column 4). If, during the 5-year growing period under consideration, this 0.1 tree emerged from the 24-inch class, it may be assumed to have been included with the 0.2 tree found in that class at the first count; therefore the difference, or 0.1 tree, must have remained in the 24-inch class (column 5). If this 0.1 tree remained in the 24-inch class as part of the 0.3 tree classified as 24-inch

TABLE 7.—*Illustration of a separate estimate of periodic diameter growth for each diameter class deduced solely from the stand data from successive inventories, assuming the hypothesis of tree movement is acceptable*

[Adapted from Meyer, 1935] [1]

Diameter class (inches)	Count		Movement		Combination		Ratio or movement factor	5-year growth in diameter	
	First	Second	Growing out	Remaining	Growing out	First and second counts		Deduced	Measured
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	Trees per acre	*Trees per acre*	*Trees per acre*	*Trees per acre*	*Trees per acre*	*Trees per acre*	*Percent*	*Inches*	*Inches*
26	-------	0.1	-------	-------	0.1	0.1	100.0	-------	-------
24	0.2	.3	0.1	0.1	.3	.5	60.0	1.2	1.4
22	.3	.3	.2	.1	.4	.6	66.7	1.3	1.3
20	.3	1.2	.2	.1	1.3	1.5	86.7	1.7	1.2
18	1.9	3.2	1.1	.8	3.5	5.1	68.6	1.4	1.2
16	4.0	5.6	2.4	1.6	6.4	9.6	66.7	1.3	1.2
14	6.7	8.3	4.0	2.7	9.6	15.0	64.0	1.3	1.2
12	10.2	10.3	5.6	4.6	11.3	20.5	55.1	1.1	1.1
10	11.6	13.1	5.7	5.9	12.9	24.7	52.2	1.0	1.0
Ingrowth	-------	-------	7.2	-------	-------	-------	-------	-------	-------
Total or average	35.2	42.4	-------	-------	45.8	77.6	59.0	1.2	-------

[1] Only the first inventory has been made so far in actual practice. Data from line 8, table 2, appear above in column 2. To represent the second inventory (column 3) are the data from line 13 of table 2 plus the mortality allowance. The figures in column 10 are from line 7 of table 2. Columns 4 to 8 contain computations leading to the results shown in column 9.

at the second count, the difference (0.2) must have grown out of the 22-inch class (column 4). This 0.2 probably was included with the 0.3 tree first found in the 22-inch class. If 0.2 of this 0.3 emerged, then 0.1 remained classified as 22-inch (column 5). Subtracting this 0.1 from the 0.3 tree found at the second count leaves 0.2 which must have grown out of the 20-inch class (column 4). The same procedure is continued in like manner until columns 4 and 5 are completely filled.

In brief, for a given diameter class the figures for movement status (columns 4 and 5) are derived from those for inventory (columns 2 and 3) in the following order: (1) Those growing out are derived from counts of the class above; (2) these emerging trees are subtracted from those present at the first count to get the remainder in the class; (3) deducting this remainder from the second count reveals the number that rose from the class below.

The last figure for column 4 shows ingrowth (7.2), which should equal the difference between the totals of columns 2 and 3.

The figures for each class (in column 6) are the average numbers of trees growing out plus those entering from below (column 4). This summation of outgrowth and ingrowth by classes Meyer termed "double rising." The figures for each class in column 7 are the sums of those entered in columns 2 and 3 for the same class. These sums Meyer termed "double effective." Figures in columns 6 and 7 form the ratios, or movement factors entered in column 8.[21] The results of multiplying the diameter-class interval by the movement factors (column 8) are the final figures for diameter growth (column 9). In the 26-inch class the scarcity of trees precludes any estimate of the rate of diameter growth.

[21] The reverse use for this type of movement factor was illustrated in table 1.

Degree of Accuracy To Be Expected

When these estimates (column 9) are compared with the average results of direct measurements of growth (column 10), it may be seen that while the last 2 agree exactly, most of the others are a fraction of an inch different. Those which failed to agree are for the larger diameter classes, in which trees are not so abundant—less than 10 per acre. This agrees with Meyer's observation that results were less accurate for the larger diameter classes.

Huffel (*25*), a French critic of this method, feared that results were not sufficiently accurate to justify the expense of frequent enumerations in large forests. According to him, inventories are frequently 5 to 7 percent incorrect, and a timber cruise 7 percent high followed by another 7 percent low may result in an error of 150 to 200 percent in increment. This is most likely to happen when dealing with slow growth or short periods. In his later years Gurnaud himself favored longer cutting cycles for the sake of the greater interval between inventories.

Regarding errors of this kind, which must be faced in applying the inventory method, Meyer (*30, pp. 803–804*) says:

> Roughly, the mean error of the calculated periodic increment will equal the square root of the sum of the squares of the mean errors in the diameter measurements at the time of the two inventories. Since the periodic increment is directly proportional to the number of years in the period, the longer the period the smaller the percentage of the error. Also, the larger the number of trees measured, the smaller this percentage will be.
>
> Obviously, the period between the two inventories should not be too short—with a mean annual growth of 2 or 3 per cent, not less than 6 to 10 years. * * * The method as applied in Switzerland works with an accuracy of 2 to 5 per cent (mean error) of the increment, if the periodic increment is about 20 per cent of the stand volume.
>
> * * * * * * *
>
> The calculation of the periodic increment based an non-permanent strips will be rather difficult, because the mean error in the estimated volume of the forest is comparatively high. This will cause the error in the increment to be still higher. In this case growth studies based on increment cores will give better results, although a new difficulty is introduced by the lack of direct measurement of dead and removed trees.

D'Alverny (*2*) recognizes that certain well-known authors have condemned increment calculation based on enumerations as inaccurate, but believes that the theorists have exaggerated the magnitude of measurement uncertainties, and that wherever work is carried out efficiently such deviations need not be considered in the same class with, or as important as, the variations in the increment measured. He states that in ordinary practice the volume error of inventory approximates 2 percent. In estimating annual production, the relative error varies inversely with the interval covered and the square root of the area involved. The upper limit of this relative error may be expressed by the formula: $e=\frac{13.5}{p\sqrt{s}}$, where e=error in cubic meters, p=period in years, and s=area in hectares. Thus, for an error in growth of half a cubic meter per hectare (about 7 cubic feet per acre), the denominator must approximate 27; and, disregarding fractions, sample combinations of areas and intervals fulfilling the requirements would be:

3 hectares (7.4 acres) and 16 years
10 hectares (24.7 acres) and 9 years
15 hectares (37.1 acres) and 7 years

This gives some conception of what may be expected from the method of recurring inventories in estimating periodic annual growth on common compartments. He admits that absolute precision is a "will-o'-the-wisp" in such calculations, warns that we had better be satisfied with practical solutions, and concludes that continuous application of "controle" by various forest owners and forest managers has furnished the best proof of the practical accuracy of its results.

Du Pasquier (*13*, *14*) has warned of errors resulting from the application of the inventory method to subnormal even-aged forests like some of our southern longleaf-slash pine forests. He cautions us against a misinterpretation of increment because of the element of ingrowth in such a forest, particularly where the ingrowing trees are grouped in masses of young timber. The danger is that an exaggerated estimate of present growth—unwarranted because it consists too largely of a temporarily above-normal supply of small ingrowing timber of low value—will lead to overoptimistic predictions of yields. Similar conclusions were reached by another French writer (*22*) at about the same time. It is obviously advisable to record separately all increment resulting from ingrowth in order that such misinterpretations may be avoided.

Recurring inventories for production control are also used in Germany. Fritzsche (*15*) recently reported his comparison of complete calipering, both rapid and deliberate, with partial cruising based on sample strips or plots. Complete and attentive calipering, with precautions to avoid errors from known sources, presumably was most accurate, but prohibitive in cost. Complete coverage under instructions to work hurriedly greatly reduced the expense, of course, but still cost more than the common sampling methods. The cost of the rapid complete inventory appeared to be justified, however, and it was chosen as the most efficient method tried. In like manner the present study is being continued by using rapid 100-percent ocular estimates by log lengths and grades, with field checks made currently to correct previously unsuspected personal, systematic, and noncompensating errors, in experimental forest cruising.

Silvicultural Systems and Types of Forest

Controversy as to the suitability of the inventory method of determining forest growth apparently has been stimulated in France by the divergent opinions of foresters using contrasting systems of management for quite different kinds of forests. It is pertinent, therefore, to consider whether the type of stand and its silvicultural treatment impose any serious limitations on the inventory method.

The method seems to have been applied most widely to tolerant coniferous species in irregular all-aged forests of selection form. In Switzerland, De Luze (*28*) reported the method well adapted to alpine forests but not suited to plateau forests. According to him, the natural reproduction in oak forests suffers too much from the use of short cutting cycles,[22] although in the natural continuous forest (*Dauerwald*) Schaeffer (*34*) reports that cycles even shorter than 10 years are growing in favor. Short cycles imply light cuts at frequent intervals and a widely distributed harvest as in the selection system. Under such a system, some concern may be felt for the reproduction of tree species that are relatively intolerant of shade. While groups of trees may have to be removed to get some kinds of seedlings started, such trees are usually not removed in groups merely to facilitate the development of saplings. Regarding the relative rates of development of young growth as affected by silvicultural systems, D'Alverny (*1*) wrote that it is probable that in an even-aged forest new growth develops more rapidly than in a selection forest, so that in the smaller size classes trees are younger in an even-aged forest than in a comparable selection forest. In the larger size classes, however, the trees are younger in the selection forest. From the time that the selection-forest reserve trees are released, they develop more rapidly, catching up with and then growing beyond the same-aged trees in an even-aged forest series on similar sites. Prejudiced against Gurnaud's method, Schaeffer (*33*) confessed his purpose in visiting a certain forest badly depleted in 1863 and reconstructed during the next 18 years by the "methode du controle" was the secret desire to confirm his objections. Even with this admittedly biased, unfavorable attitude, however, he was apparently induced to change his mind, for he reported that by a study of the forest and its management schedule he had become disillusioned and convinced of its practical success.

De Coulon (*11*) criticized the "methode du controle" as having received more emphasis than its importance warrants. He thought well of the part that deals with silvicultural selection, but felt that too rigid an interpretation of control was a dangerous misconception. He warned that in managing a forest any forester who becomes a slave to any system of bookkeeping is unworthy of his trust and stated that no matter how highly developed a system of control may become, the free selection of trees to be cut must remain an art, if forestry is to make satisfactory progress. By varying the size of areas first designated to be cut over, however, it is possible from the start to operate a forest so that silvicultural considerations remain locally dominant and yet apply an over-all control of cutting that will (through future revisions) permit proper and ultimately more intensively localized regulation of forest production.

As a practical method of controlling production in forestry, Meyer (*30*) cites five advantages and three disadvantages of the method of recurring inventories. Briefly, the advantages are: (1) Cheapness, (2) applicability to large tracts as well as to strips and plots, (3) the fact that the same field data yield growth information in terms of diameter, basal area, and volume, (4) short and simple office computations, and (5) its value both to research and practice. The disadvantages are: (1) Large numbers of trees must be measured, (2) a period of years must elapse, and (3) the diameter of trees removed must be measured.

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[22] This author certainly was not wedded to old methods of regulation, as he wrote facetiously (apparently referring to the classical formulas of Heyer, Hundeshagen, etc.): "Believe me, in our times we can have no traffic with such abstract elements as were invented by old-time lackadaisical dreamers across the Rhine."

APPLICATION OF GROWTH FORECASTS

Some timber growers who have experienced no difficulty thus far in maintaining production schedules may feel that the detailed technical matters discussed in the present report need not concern them or their forest managers. As pointed out by Biolley (*5*), sustained yield is sometimes erroneously regarded as an end in itself, but, although a worthy achievement, it is by no means the ultimate goal of forest management. Complacency in this matter is unwarranted, because a managed forest is never static, and its normal or maximum yield remains unknown, so that increased yields should be sought constantly.

Opinions as to the relative merits of the various methods of stand forecasting must remain tentative, since there has been so little opportunity to gage the accuracy (or lack of it) inherent in this kind of work. Certain features of one method, however, may make it less suitable than some other method in a given situation. For instance, the simplified stand-table-projection method, using average rates of growth and requiring the boring of fewer trees than does the dispersion method, may be chosen because of this economy alone. On the other hand, the dispersion method gives a truer, if somewhat exaggerated, picture of the details of actual growth; and if information on future distribution of size classes is needed in advance of the next regular inventory, the dispersion method certainly is to be preferred. Realizing how badly the total volume of growth predicted by either of these variations of the stand-table-projection method may be in error because of some false assumption, or because changes in rates of growth were not correctly gaged, the preference shown by some workers for the time-saving simplicity of growth-percent formulas or other short-cut methods may be fully warranted. Absolute units, however, are far better suited to an expression of the true significance for forest growth.

The method of recurring inventories, which reverses the procedure of the stand-table method, falls in a different category in that the forecasting cannot be completed in a few weeks or months. Several years of elapsed time are necessary. As a consequence, much of the uncertainty of the other methods, e. g., the mortality allowance, is neatly circumvented so far as the observation period is concerned, and therefore this method may appear less subject to error in the forecast period. If exact knowledge of changes in the distribution of trees by diameter classes is not vital, the method of recurring inventories may be preferred. Although it may not answer the demand for forecasts by the immediately available methods, it may be advocated largely because it offers so direct and simple a way to record currently the results of silvicultural management. The outstanding virtue to recommend this slowest of all methods is that it is based on the results from a long period of actual practice and experience—the only reliable guide in the long run.

Forecasts of growth find their principal use in making, checking, and revising estimates of the volume of timber that may be cut annually without jeopardizing future yields. Although a forest might be considered well regulated if there were no overcutting in volume, that is, if the total periodic cut did not exceed net growth during the same period, more than that is needed. The growing stock as a whole should be built up consistently, not only by increasing the number of trees on understocked areas, but also by making release cuttings to accelerate the development of the more valuable trees now crowded in groups. Unless this is done, the forest will positively not support occasional localized overcutting that may be silviculturally and economically desirable under certain circumstances. Parts of forests or timber stands often require a certain amount of constructively selective overcutting when first placed under management, in

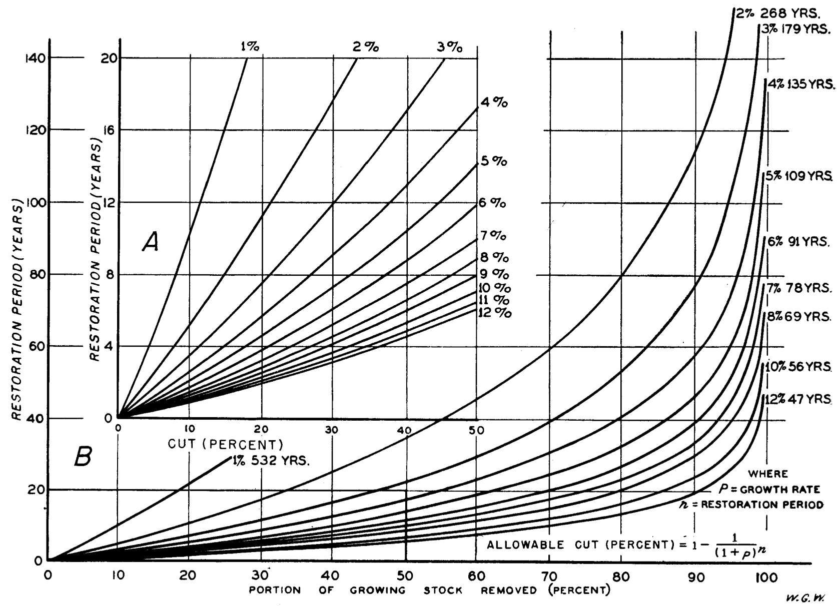

FIGURE 7.—Time required for complete restoration of growing stock after cutting. These curves represent the formula: Allowable cut in percentage$=1-\frac{1}{(1+p)^n}$ where p equals the rate of volume growth expressed as a percentage (rate of interest compounded annually) and n equals the restoration period in years. Curves are shown for average rates of growth from 1 to 12 percent. The extreme right-hand part of (*B*), for exploitation ranging up to a cut of 99½ percent of the growing stock, is included only for the sake of completeness. The useful lower left-hand part (*B*), for removal of not more than half the stock and periods not in excess of 20 years, is shown enlarged to a more adequate scale in (*A*).

order to provide, with reasonable promptness, a suitable basis for future growth in values. A sound rule for the forest manager is to "save growing stock in bad times and save money in good times," so that the business is equalized and stabilized throughout the years. (*7*).

In marking timber for cutting, it is helpful to know something of the amount that may be cut locally without exceeding the amount that can be restored by growth on the same area before the next periodic cut. Table 8, which is portrayed graphically in figure 7, is designed to show the maximum proportion of the volume of present stands that may be removed with the expectation of full restoration in a given period, assuming that growth can be maintained at the rate forecast. This table should be useful if applied only as a general guide. Obviously the response of a forest parallels no such precise mathematical formula. While cutting brings a known reduction in wood capital, it brings also an indefinite and temporary increase in growth percentage. Thus in using table 8 the growth percentage should be chosen conservatively so as to approximate, if possible, the average normal fluctuations in rate that always accompany intermittent cuttings. Since a high degree of precision is impossible in these calculations and since the growing capacity of forests is changing constantly, best results are to be had from repeated verifications of rates of growth. The lower half of table 8 is included for academic interest only. For all but the most intolerant species, short cutting cycles, and the light cuts necessary to adhere to them, are recommended. By this means, and by the well-considered revision of management plans, sound experience in silviculture and procedures in forest regulation can be attained most rapidly.

TABLE 8.—*Percentage of volume of forest growing stock removable*[1] *and theoretically restorable at growth rate p in a cutting cycle of n years*

Cutting cycle *n* years	Assumed maintainable compound-interest rates of growth *p*—											
	1	2	3	4	5	6	7	8	9	10	11	12
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
1	1	2	3	4	5	6	7	7	8	9	10	11
2	2	4	6	8	9	11	13	14	16	17	19	20
3	3	6	8	11	14	16	18	21	23	25	27	29
4	4	8	11	15	18	21	24	26	29	32	34	36
5	5	9	14	18	22	25	29	32	35	38	41	43
6	6	11	16	21	25	30	33	37	40	44	47	49
7	7	13	19	24	29	33	38	42	45	49	52	55
8	8	15	21	27	32	37	42	46	50	53	57	60
9	9	16	23	30	36	41	46	50	54	58	61	64
10	9	18	26	32	39	44	49	54	58	61	65	68
11	10	20	28	35	42	47	52	57	61	65	68	71
12	11	21	30	38	44	50	56	60	64	68	71	74
13	12	23	32	40	47	53	59	63	67	71	74	77
14	13	24	34	42	49	56	61	66	70	74	77	80
15	14	26	36	44	52	58	64	68	73	76	79	82
16	15	27	38	47	54	61	66	71	75	78	81	84
17	16	29	39	49	56	63	68	73	77	80	83	85
18	16	30	41	51	58	65	70	75	79	82	85	87
19	17	31	43	53	60	67	72	77	81	84	86	88
20	18	33	45	54	62	69	74	79	82	85	88	90
25	22	39	52	62	70	77	82	85	88	91	93	94
30	26	45	59	69	77	83	87	90	92	94	96	97
35	29	50	64	75	82	87	91	93	95	96	97	98
40	33	55	69	79	86	90	93	95	97	98	98	99
45	36	59	74	83	89	93	95	97	98	99	99	[2] 99
50	39	63	77	86	91	95	97	98	99	[2] 99	[2] 99	------
60	45	70	83	90	95	97	98	[2] 99	[2] 99	------	------	------
70	50	75	87	94	97	98	[2] 99	------	------	------	------	------
80	55	79	91	96	98	99	------	------	------	------	------	------
90	59	83	93	97	99	[2] 99	------	------	------	------	------	------
100	63	86	95	98	[2] 99	------	------	------	------	------	------	------
110	67	89	96	99	------	------	------	------	------	------	------	------
120	70	91	97	[2] 99	------	------	------	------	------	------	------	------
150 [2]	78	95	99	------	------	------	------	------	------	------	------	------

[1] Allowable cut $=1-\frac{1}{(1+p)^n}$

[2] When practically the whole stand (99½ percent +) of timber is cut in one operation, the theoretical time in years (*n*) needed for restoration under each growth rate is as follows: (1) 532 (2) 268, (3) 179, (4) 135, (5) 109, (6) 91, (7) 78 (8) 69, (9) 61, (10) 56, (11) 51, (12) 47.

SUMMARY AND CONCLUSION

A working knowledge of methods suitable for short-term forecasting of timber growth in irregular stands is essential when a forest is first placed under management. In situations where ingrowth is not large and increment in volume is sought only for the forest as a whole, a simple method of projecting stand tables into the future is adequate, provided that any existing trends of change in average rates of diameter growth are recognized and allowed for. The neglect of possible deceleration in uncut stands or of acceleration in heavily cut stands can be a source of large error. As a means of expressing rates of timber growth, percentage is reliable only as the static expression of an existing momentary relationship. For this and other reasons it is often preferable to express volume growth in absolute units. Prediction of timber growth by projecting stand tables is less necessary after conservative cutting practices have become well established. For properties already under some form of forest management, the recurring-inventory method is a promising means of determining current growth and regulating the cut. A knowledge of both techniques should contribute to the sound regulation of American forests.

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U. S. GOVERNMENT PRINTING OFFICE: 1941